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(54) **IMAGING LENS AND SOLID STATE IMAGING DEVICE**

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G02B 9/34	(2006.01)
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CPC *H01L 27/14627* (2013.01); *G02B 3/0056* (2013.01); *G02B 13/0035* (2013.01); *H04N 5/2254* (2013.01); *H04N 5/2257* (2013.01); *G02B 15/173* (2013.01)

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CPC H04N 5/2254; G02B 13/004; G02B 13/0015; G02B 9/34; G02B 13/18; G02B 13/16; G02B 13/001; G02B 5/005; G02B 13/0035; G02B 15/173; G03B 9/02

USPC 359/715, 716, 738–740, 747, 748, 773, 359/784, 785, 798; 348/360
See application file for complete search history.

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Primary Examiner — Evelyn A Lester
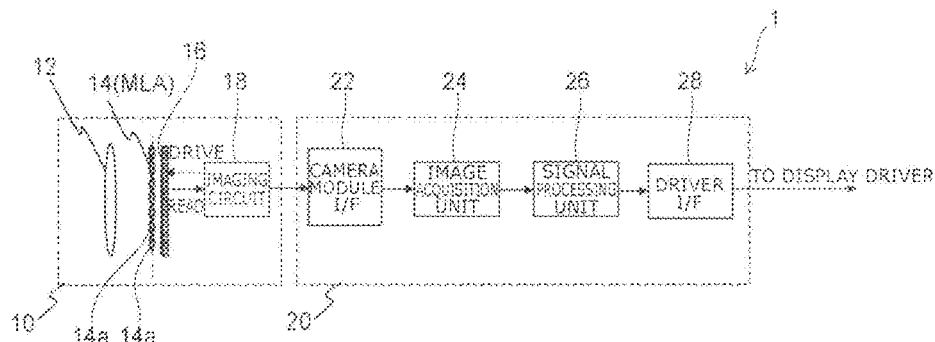(74) *Attorney, Agent, or Firm* — Oblon, McClelland, Maier & Neustadt, L.L.P.

(57) **ABSTRACT**
According to one embodiment, an imaging lens includes a first optical system and a microlens array. The first optical system includes an optical axis. The microlens array is provided between the first optical system and an imaging element. The microlens array includes microlens units provided in a first plane. The imaging element includes pixel groups. Each of the pixel groups includes pixels. The microlens units respectively overlap the pixel groups when projected onto the first plane. The first optical system includes an aperture stop, and first, second, and third lenses. The first lens is provided between the aperture stop and the microlens array, and has a positive refractive power. The second lens is provided between the first lens and the microlens array, and has a negative refractive power. The third lens is provided between the second lens and the microlens array, and has a positive refractive power.

15 Claims, 29 Drawing Sheets

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  G02B 27/02 (2006.01)
  H01L 27/146 (2006.01)
  H04N 5/225 (2006.01)
  G02B 13/00 (2006.01)
  G02B 3/00 (2006.01)
  G02B 15/173 (2006.01)

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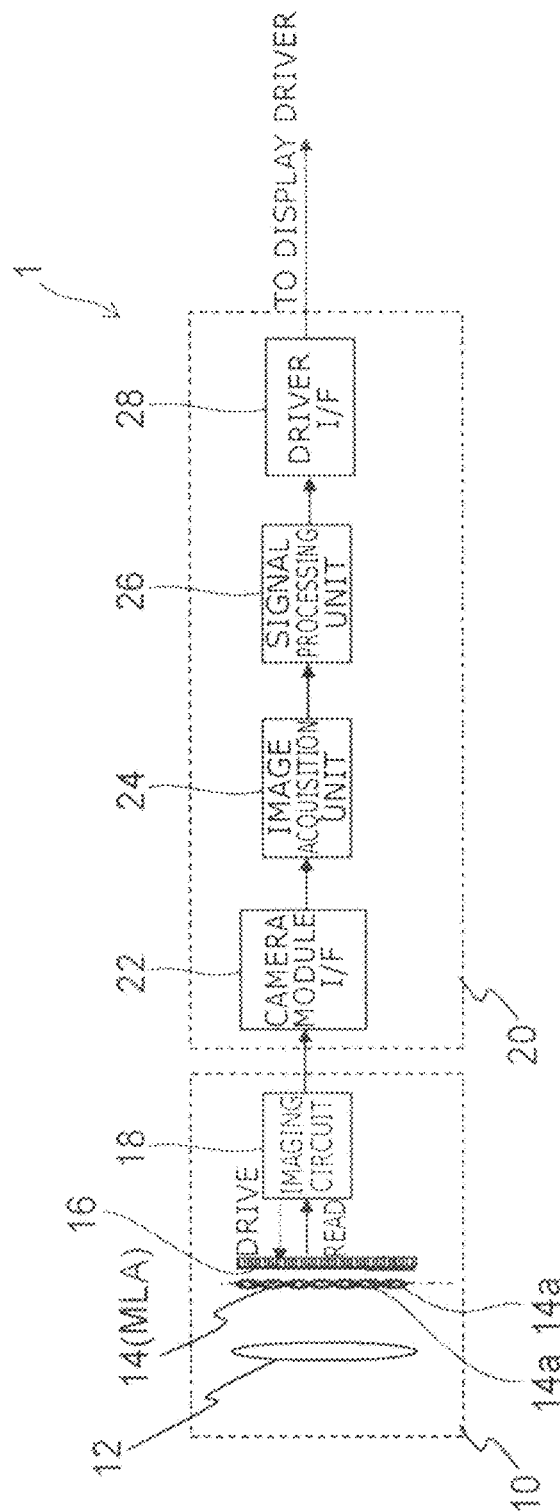Combined Office Action and Search Report issued Sep. 9, 2015 in Taiwanese Patent Application No. 103128301 (with English language translation).
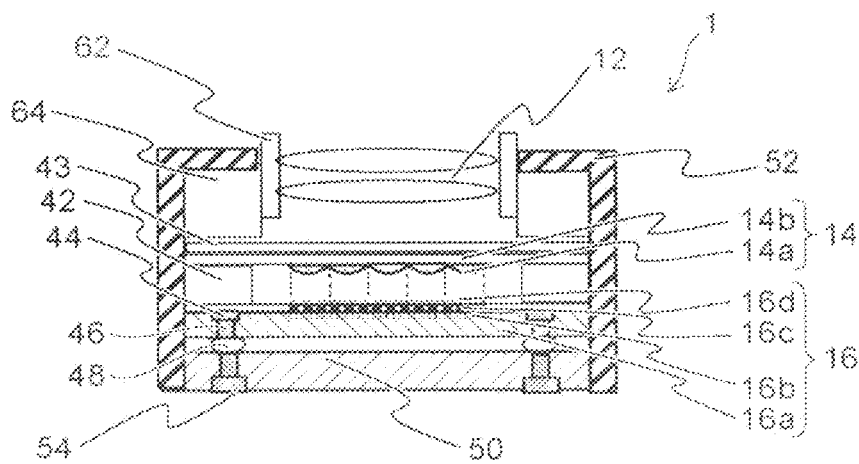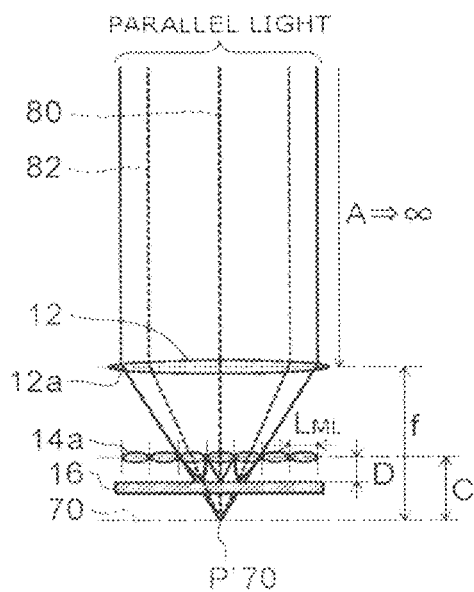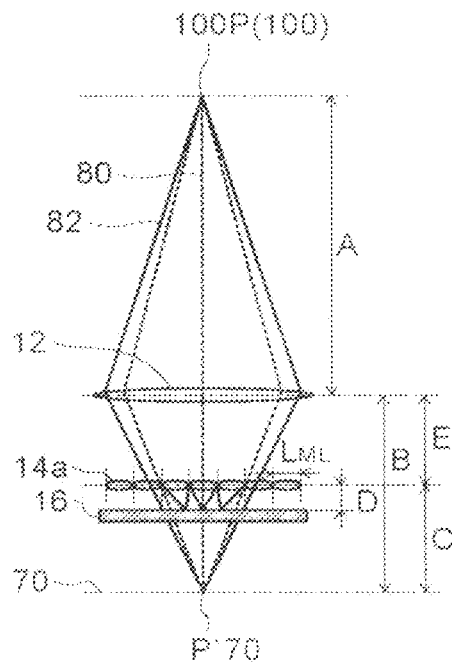
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FIG. 1

FIG. 2

FIG. 3A

FIG. 3B

FIG. 4

FIG. 5B

FIG. 5C

FIG. 5A

ENLARGING &
ARITHMETIC AVERAGE

FIG. 6C

PLENOPTIC
IMAGE

FIG. 6B

SIGNAL $S_{p1}, S_{p2}...S_{pn}$ SIGNAL : S'_p

FIG. 6D

FIG. 6E

TWO-DIMENSIONAL
IMAGE

START

S101   PLENOPTIC
OUTPUT IMAGE

S102   WHITE BALANCE
PROCESSING

S103   DEMOSAICING

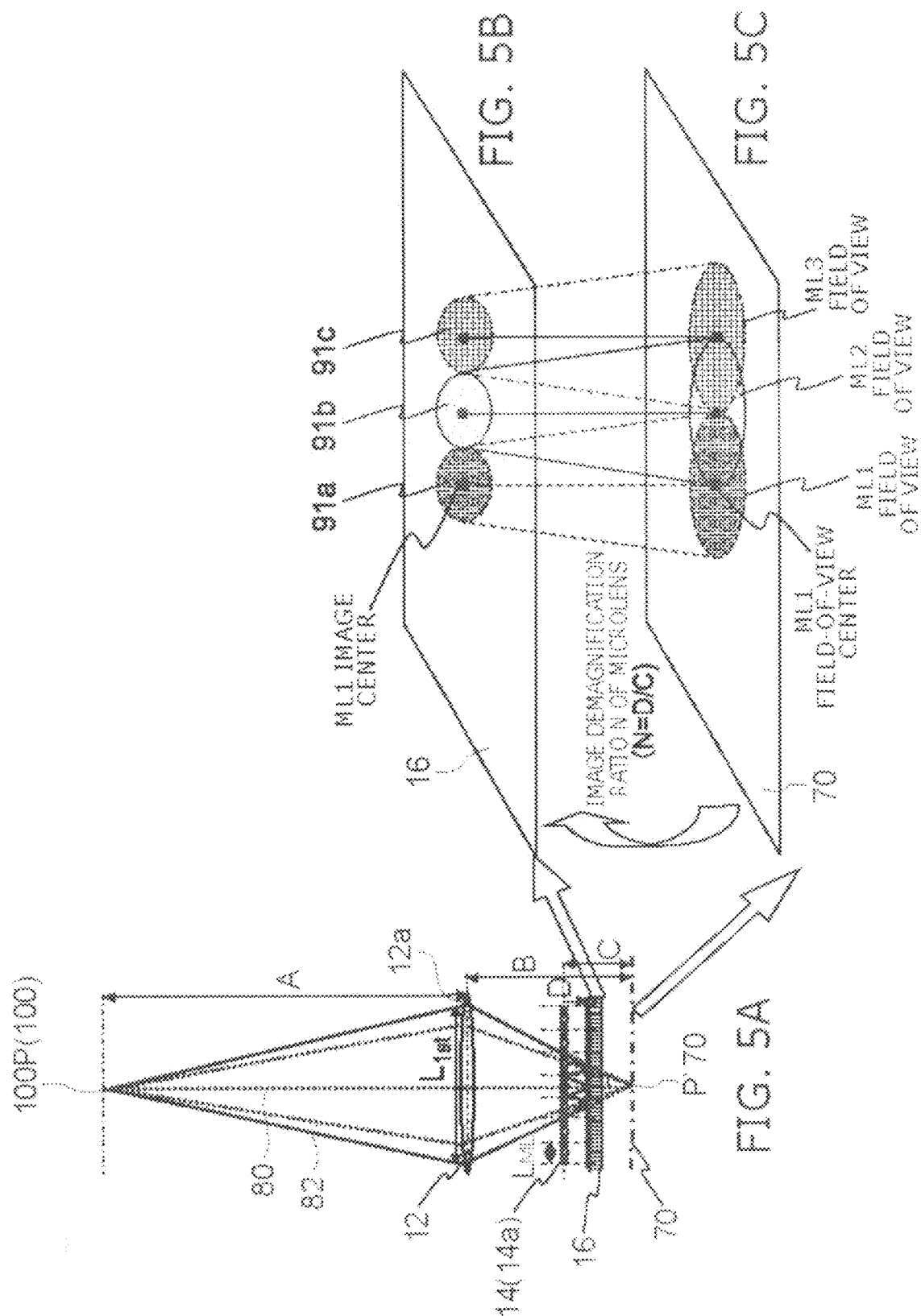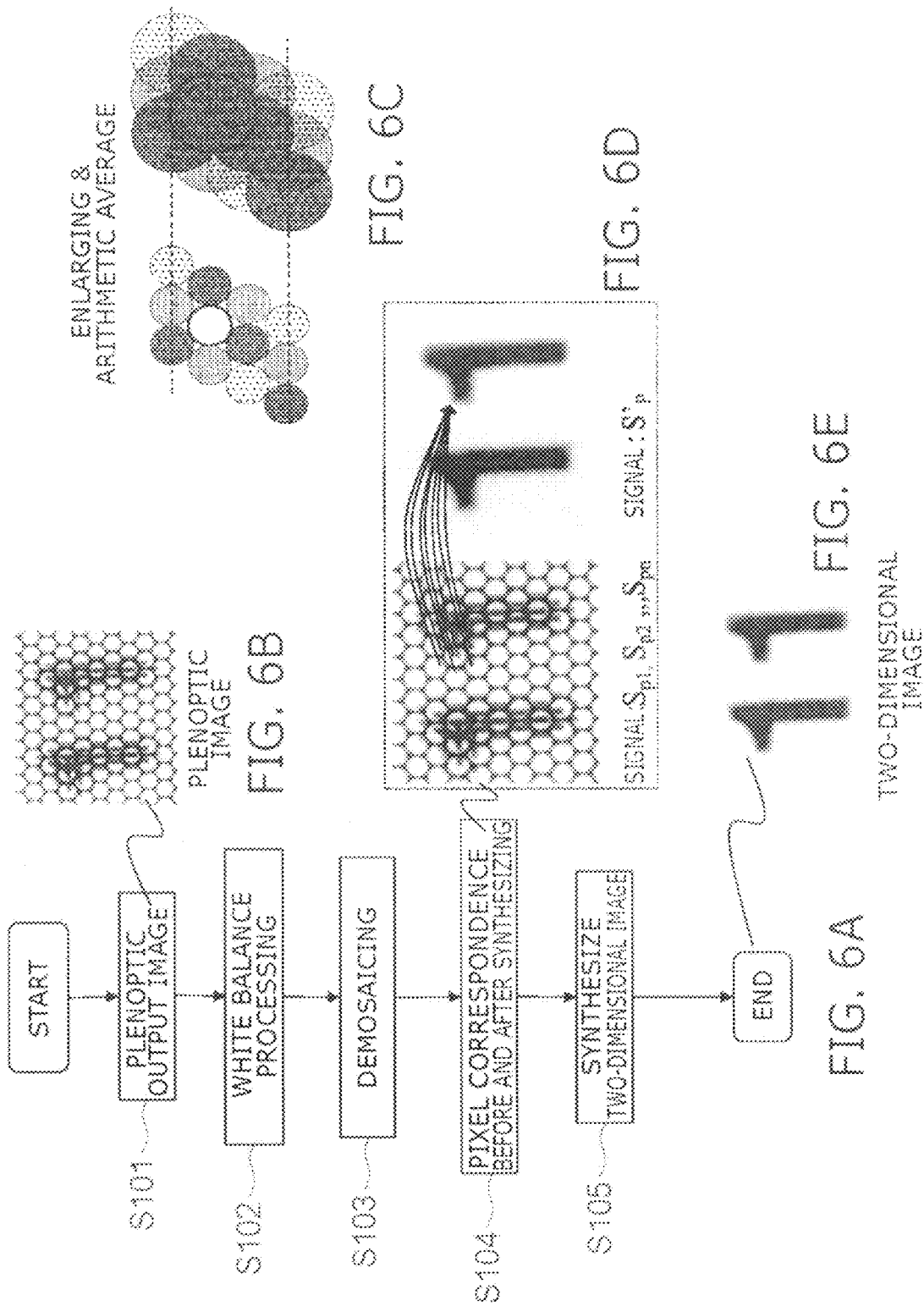S104   PIXEL CORRESPONDENCE
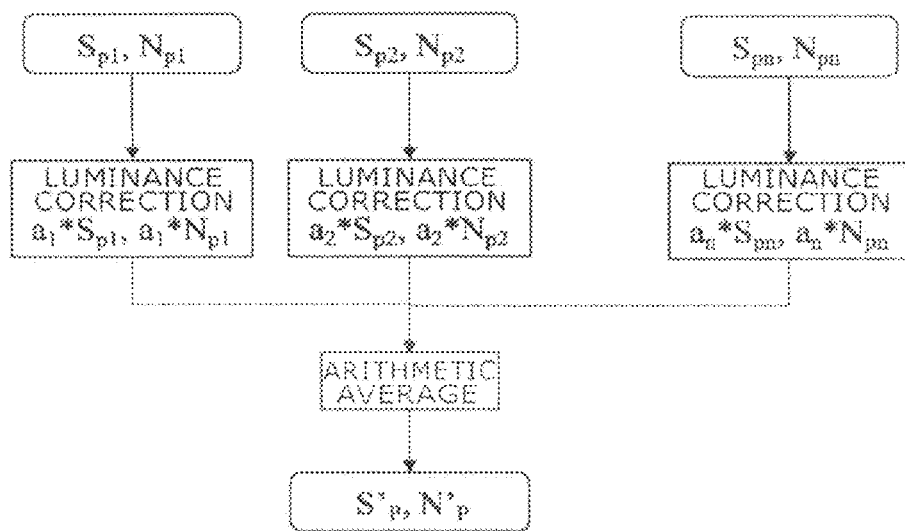BEFORE AND AFTER SYNTHESIZING

S105   SYNTHESIZE
TWO-DIMENSIONAL IMAGE

END

FIG. 6A
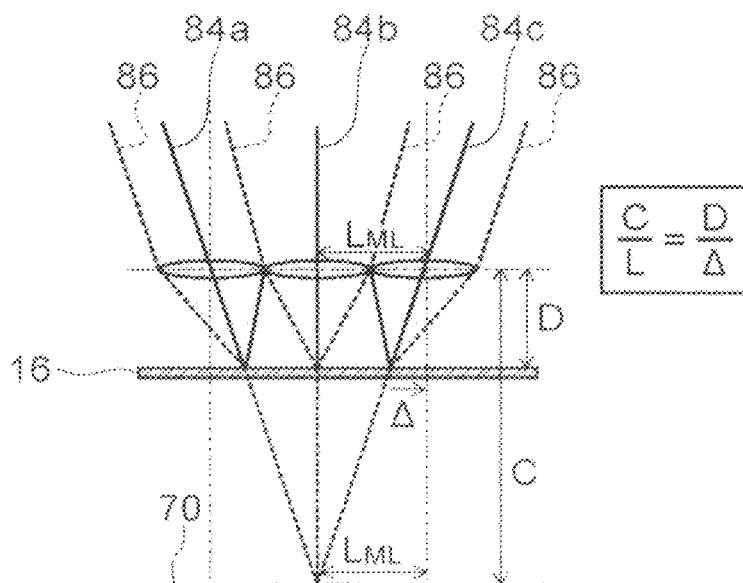
FIG. 7

FIG. 8

FIG. 9

FIG. 10

FIG. 11

IMAGING PLANE WITHOUT MICROLENS

IMAGING PLANE WITH MICROLENS

SUBPIXELS OF IMAGING ELEMENT

MICROLENS

MICROLENS SUBSTRATE

FIG. 12
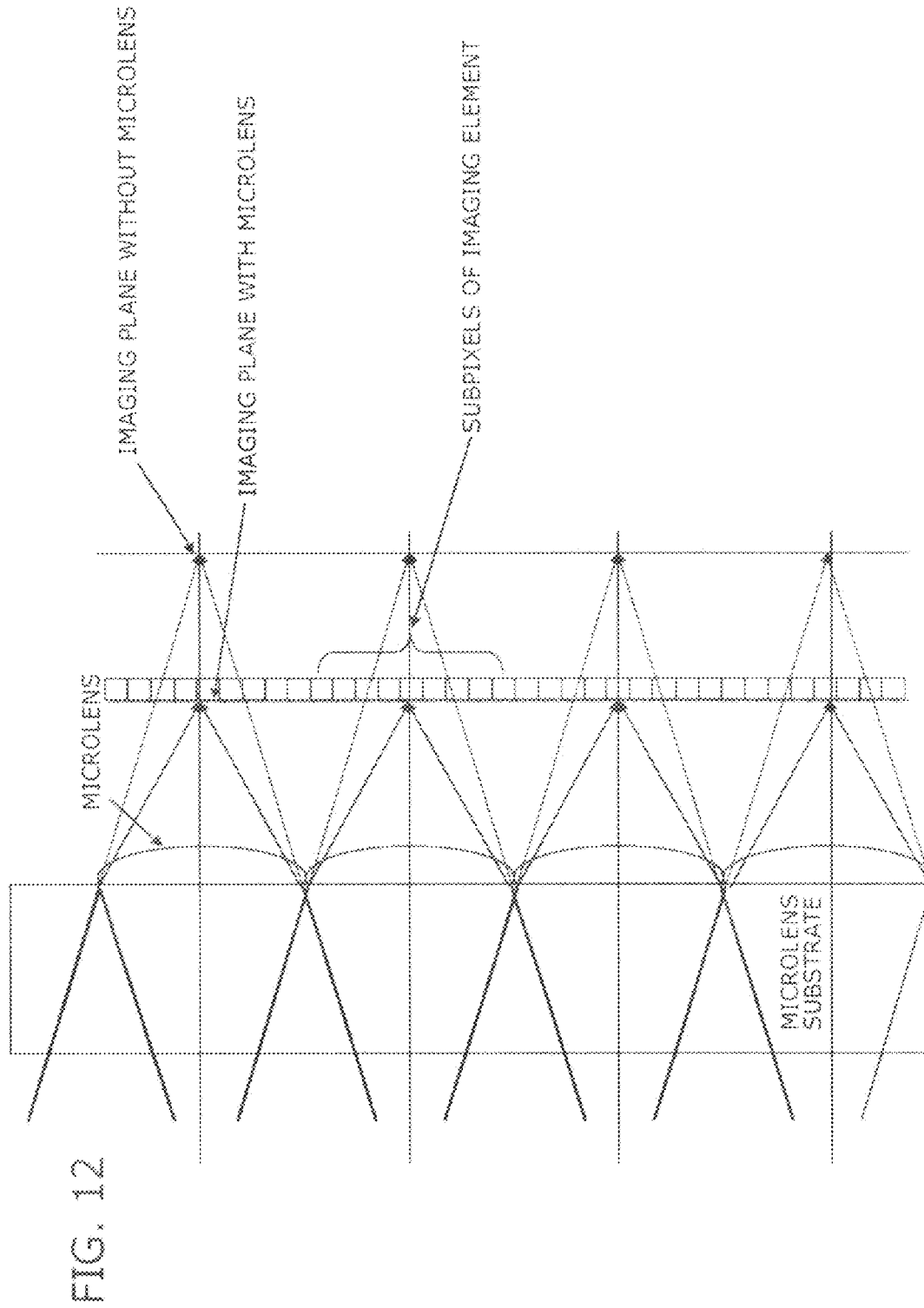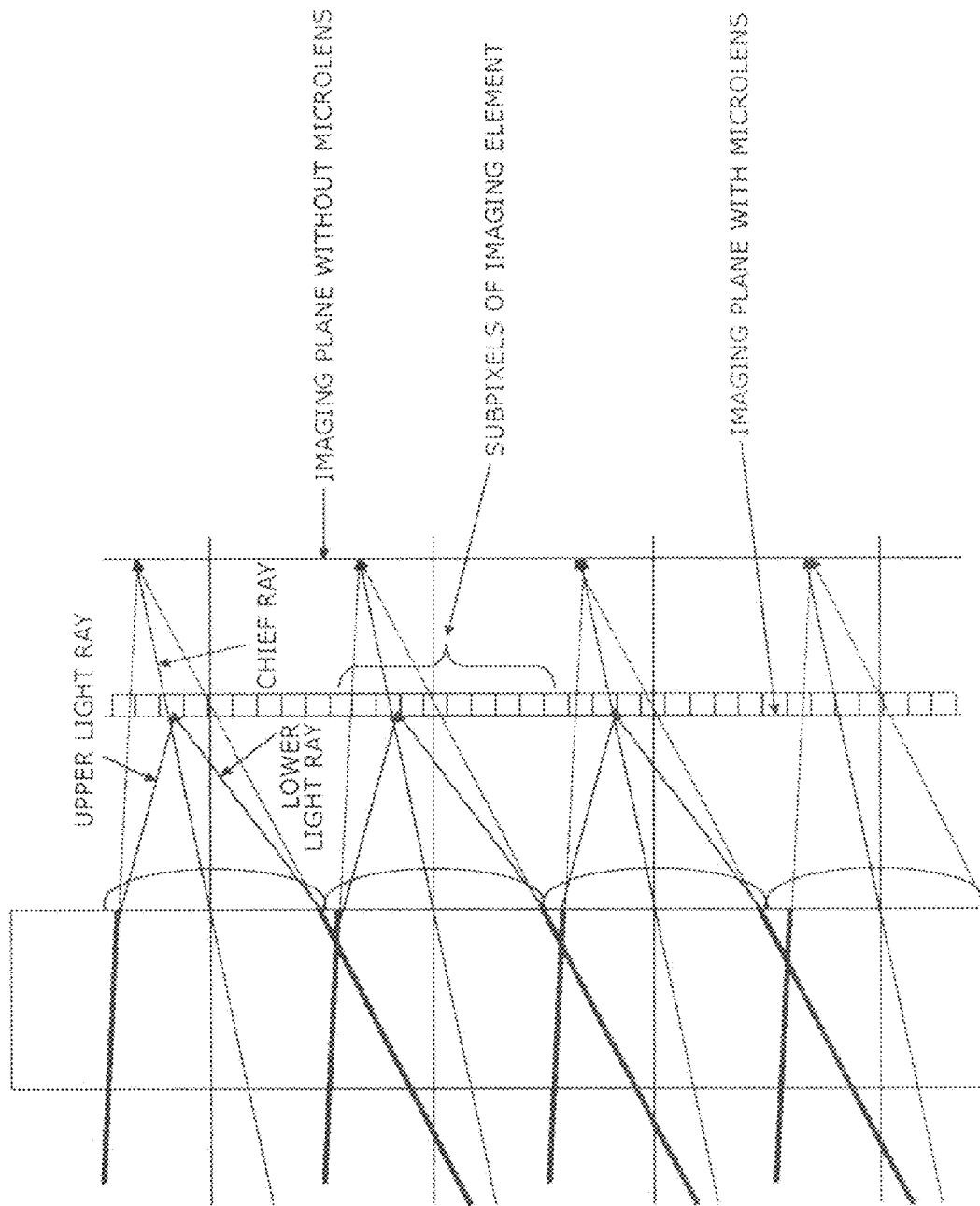
FIG. 13

FIG. 14

FIG. 15

FIG. 16

F-LINE
(λ486nm)

C-LINE   d-LINE
(λ656nm)   (λ587.6nm)

·SCALE: 20 MICRONS

OBJECT SURFACE:0.00, 20.00 (DEGREES)
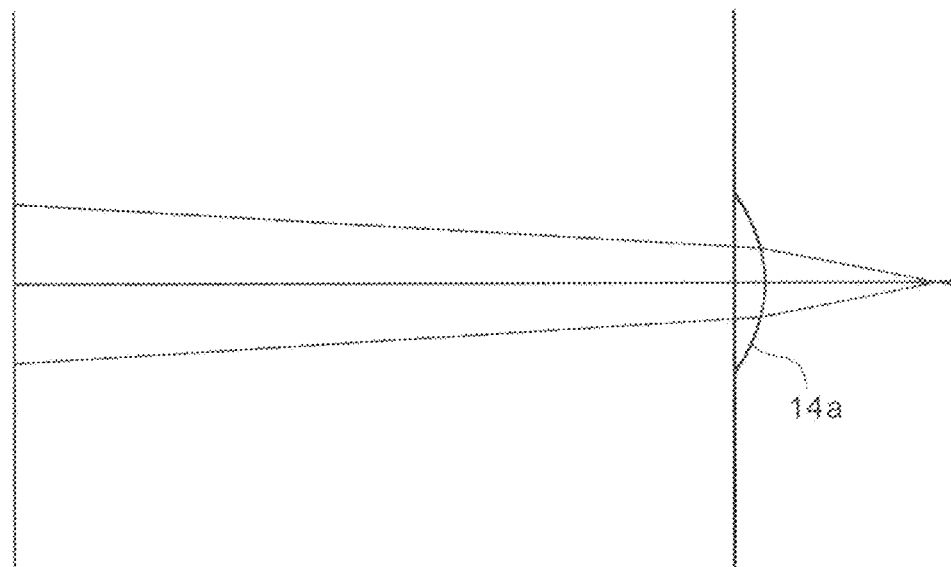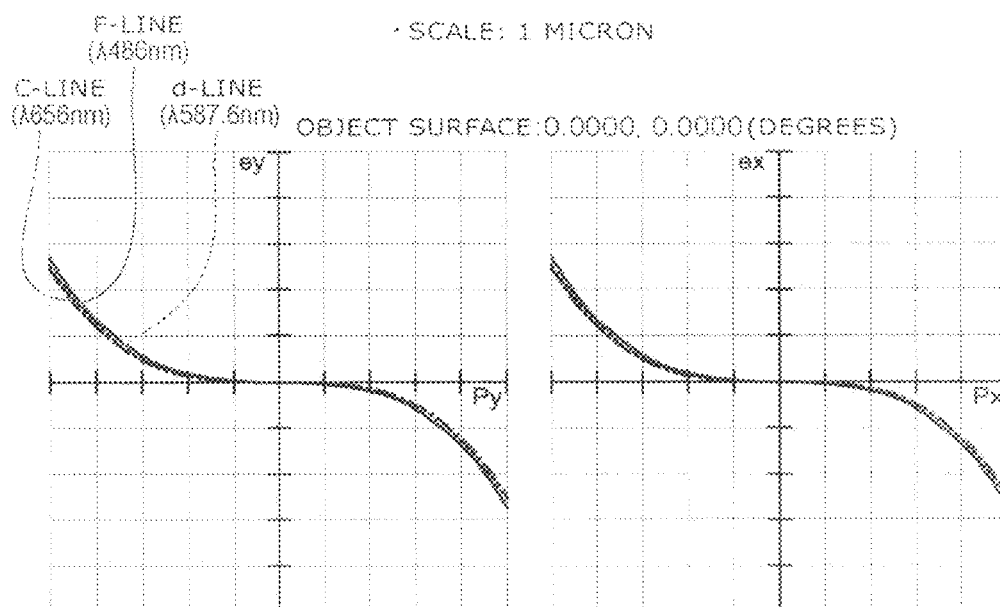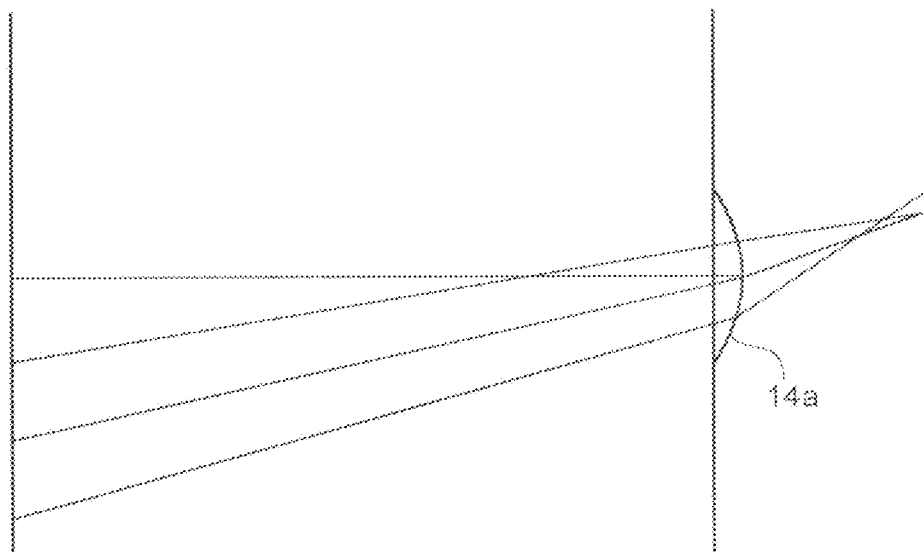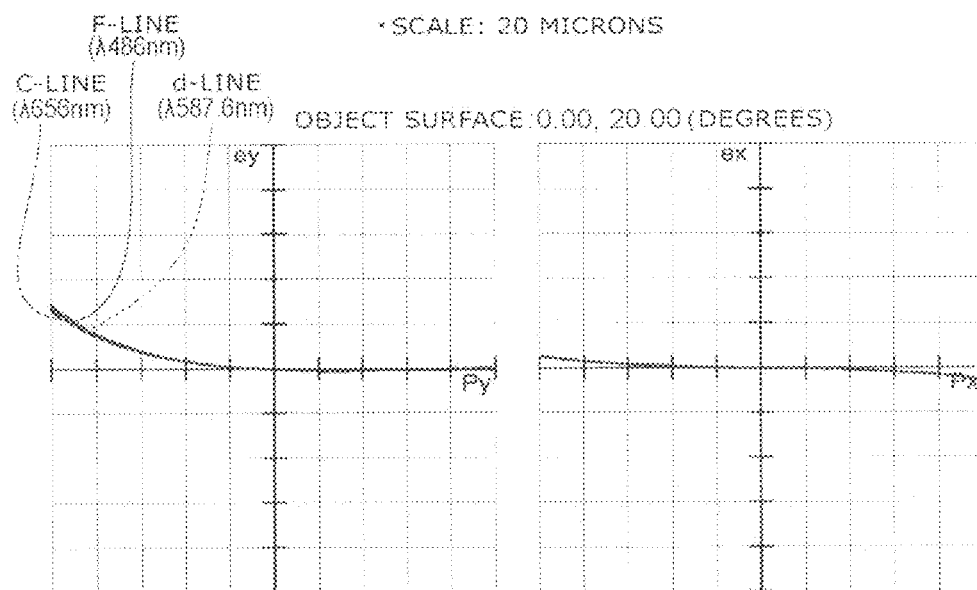
FIG. 17

FIG. 18

FIG. 19

FIG. 20

FIG. 21

F22

F-LINE   d-LINE   C-LINE

-0.1 -0.08 -0.06 -0.04 -0.02 0 0.02 0.04 0.06 0.08 0.1

Millimeters

SPHERICAL ABERRATION

FIG. 22

FIELD CURVATURE

S   T   S   S   T   T
(F-LINE) (F-LINE) (d-LINE)   (C-LINE) (C-LINE) (d-LINE)

+Y

-0.20   0.00   0.20

Millimeters

ASTIGMATIC ABERRATION

DISTORTION

C-LINE   F-LINE

d-LINE

+Y

-2   0   2

PERCENT

DISTORTION ABERRATION
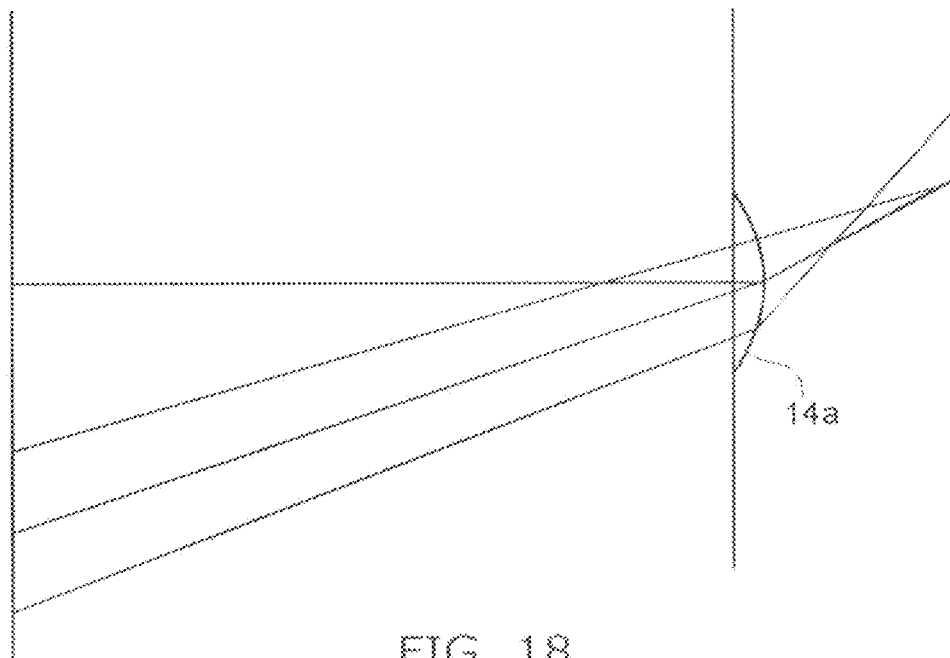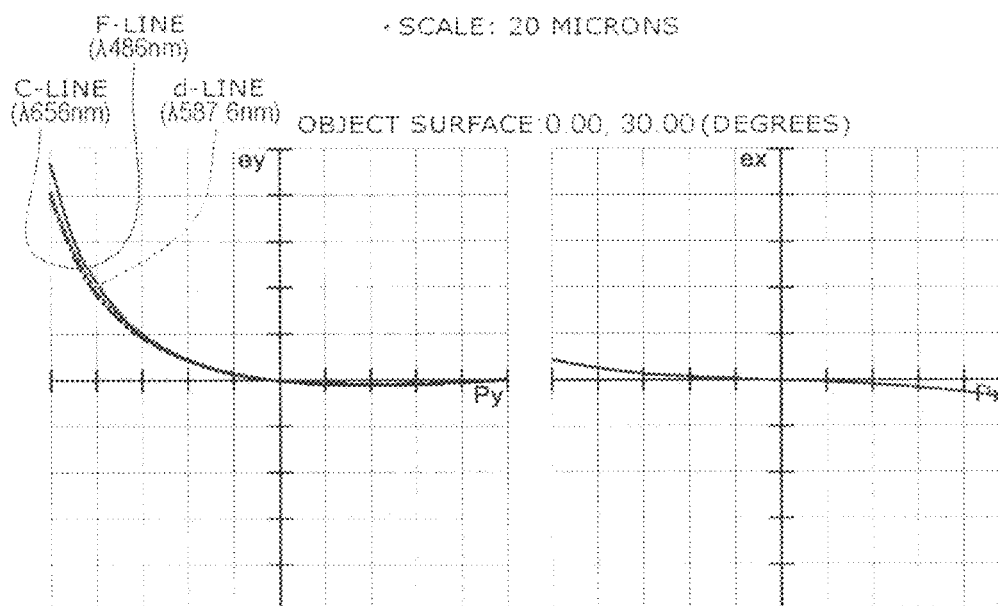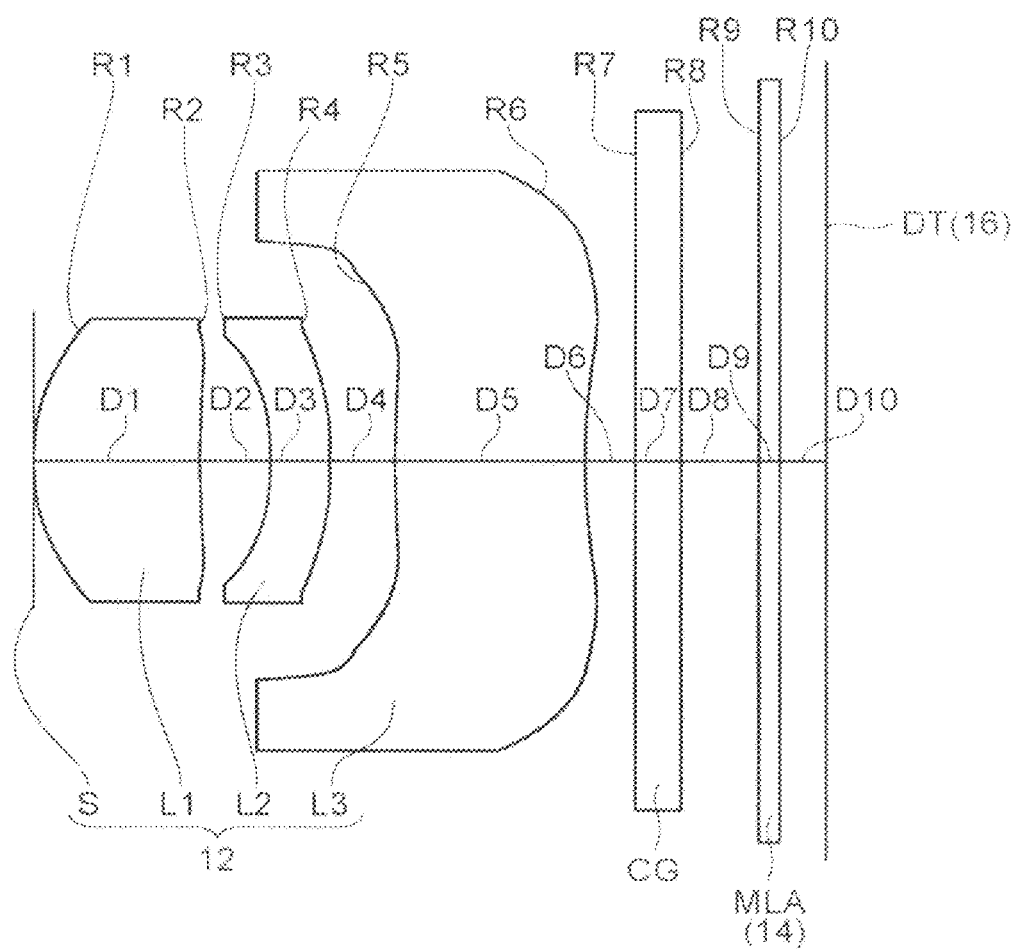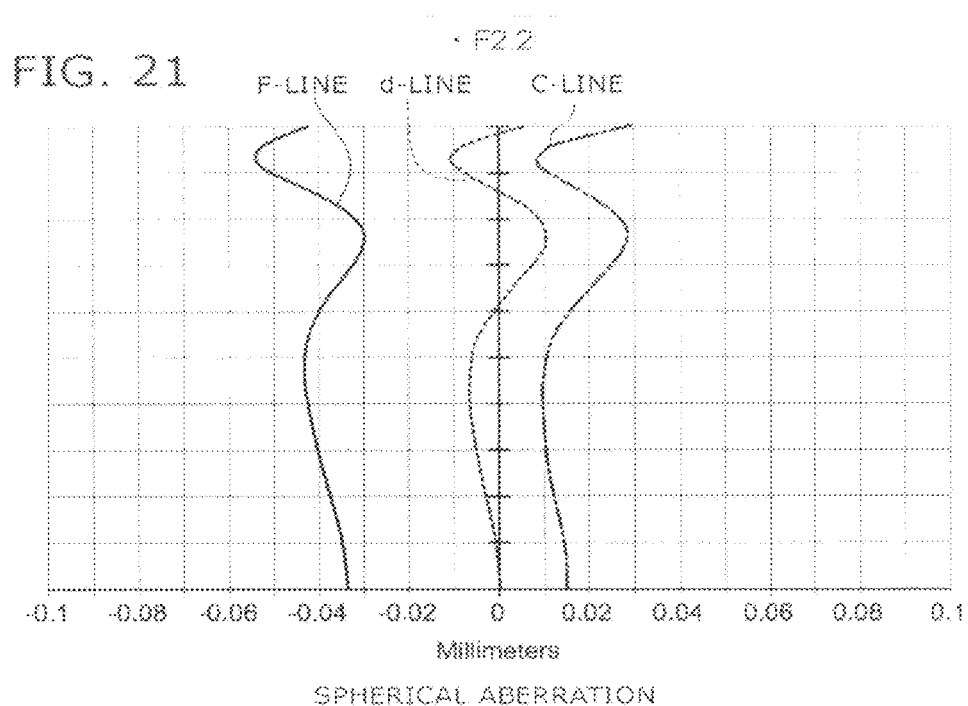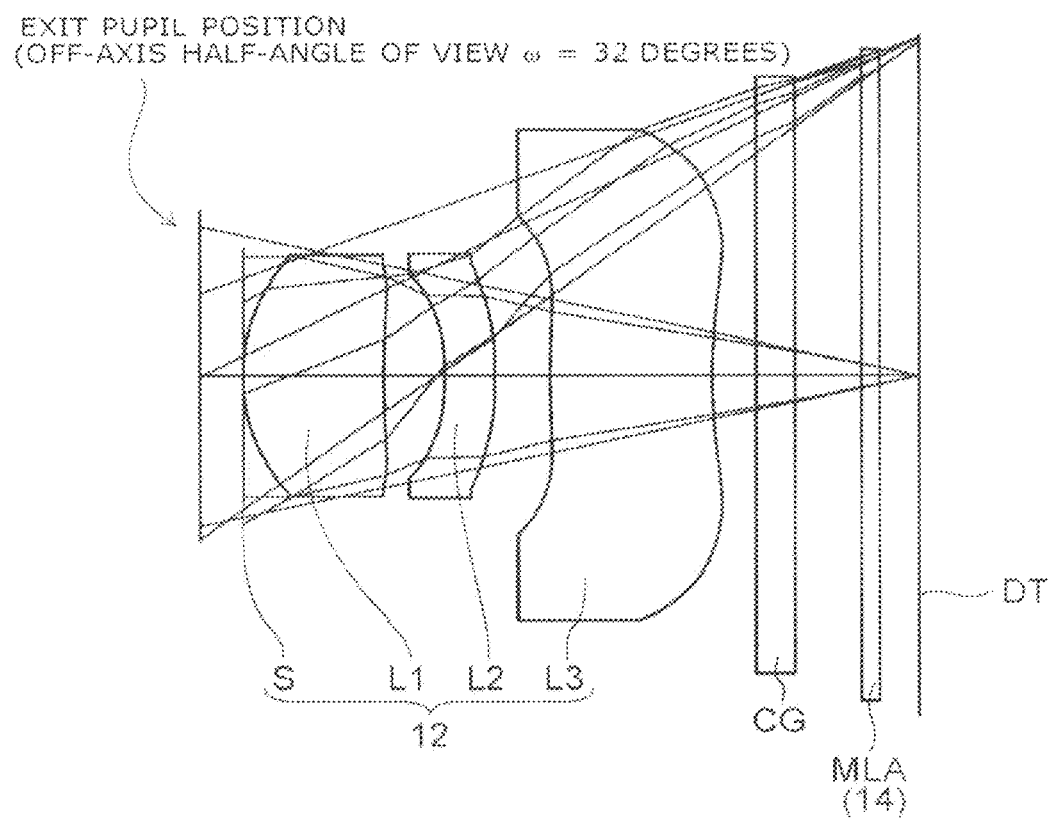
FIG. 23

LIGHT RAY X MINIMUM = -1.2432   LIGHT RAY X MAXIMUM = 1.2432
LIGHT RAY Y MINIMUM = -1.3917   LIGHT RAY Y MAXIMUM = 0.7090

* a=1.2432   b=(0.7090+1.3917)/2 = 1.05035
* ρ = | 1- 1.05035/1.2432 | = 0.155

FIG. 24

FIG. 25

FIG. 26

· F2.24

F-LINE   d-LINE   C-LINE

-0.1 -0.08 -0.06 -0.04 -0.02   0   0.02 0.04 0.06 0.08 0.1

Millimeters

SPHERICAL ABERRATION

FIG. 27

FIELD CURVATURE   DISTORTION

S   T   S   S   T   T
(F-LINE) (F-LINE) (d-LINE)   (C-LINE) (C-LINE) (d-LINE)   F-LINE   C-LINE d-LINE

+Y   +Y

-0.20   0.00   0.20   -2   0   2

Millimeters   PERCENT

ASTIGMATIC ABERRATION   DISTORTION ABERRATION

EXIT PUPIL POSITION
(OFF-AXIS HALF-ANGLE OF VIEW ω = 32.03 DEGREES)

DT

S   L1   L2   L3

12

CG

MLA
(14)
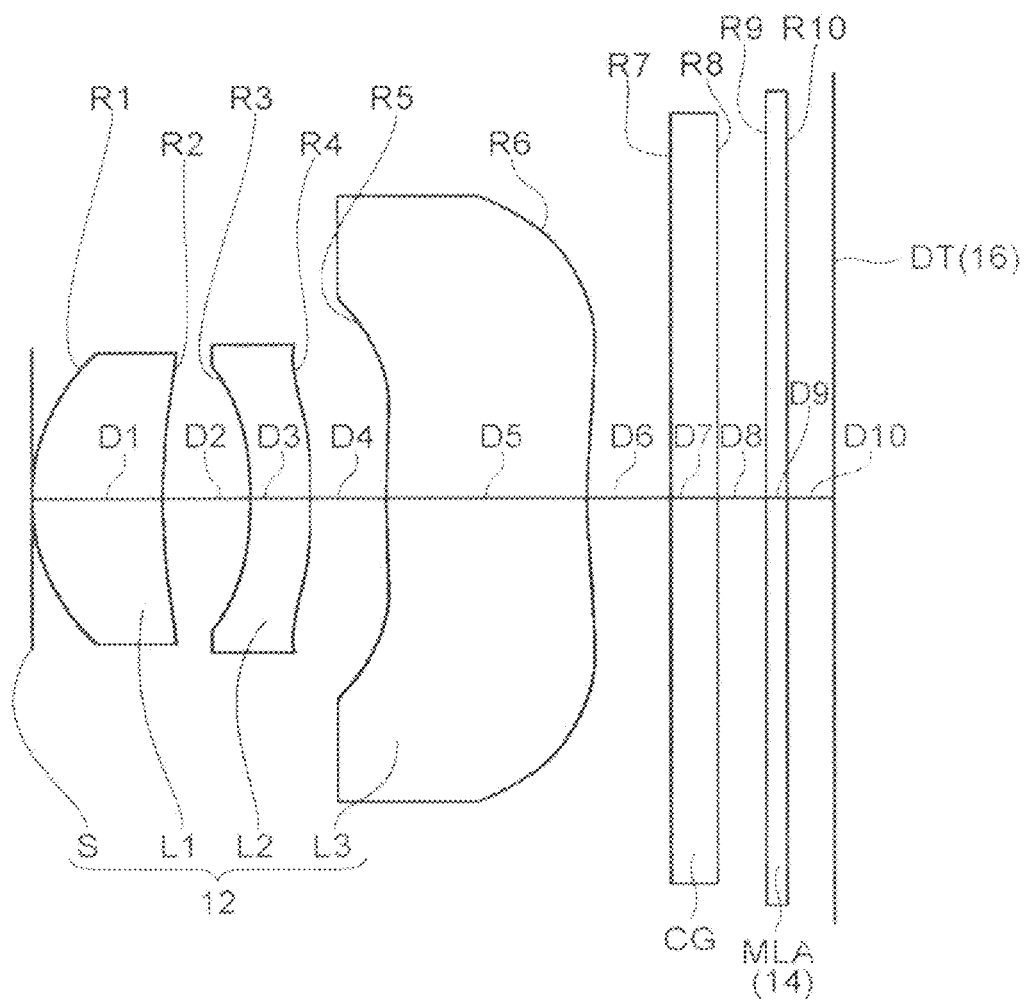
FIG. 28
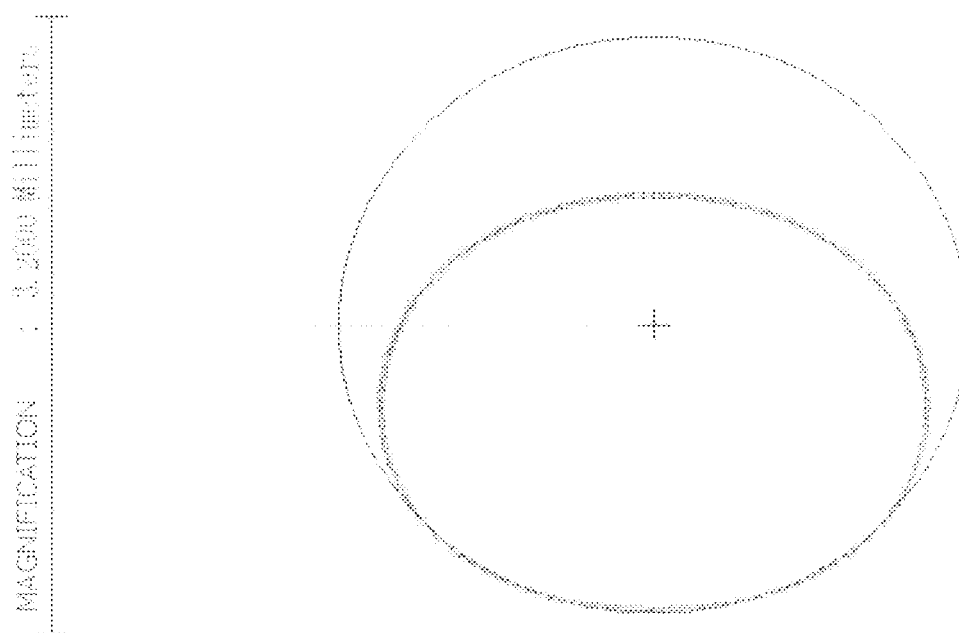
LIGHT RAY X MINIMUM =-1.2884   LIGHT RAY X MAXIMUM=1.2884
LIGHT RAY Y MINIMUM =-1.4698   LIGHT RAY Y MAXIMUM=0.6706

* a=1.2884   b=(0.6706+1.4698) /2 = 1.0702
* p = | 1-1.0702/1.2884 | = 0.169

FIG. 29

FIG. 30

FIG. 31

F2.24

F-LINE   d-LINE   C-LINE

-0.1   -0.08   -0.06   -0.04   -0.02   0   0.02   0.04   0.06   0.08   0.1

Millimeters

SPHERICAL ABERRATION

FIG. 32

FIELD CURVATURE

S   T   S   S   T   T
(F-LINE) (F-LINE) (d-LINE)   (C-LINE) (C-LINE) (d-LINE)

+Y

-0.20   0.00   0.20

Millimeters

ASTIGMATIC ABERRATION

DISTORTION

F-LINE   d-LINE   C-LINE

+Y

-1   0   1

PERCENT

DISTORTION ABERRATION

EXIT PUPIL POSITION
(OFF-AXIS HALF-ANGLE OF VIEW ω = 32.15 DEGREES)
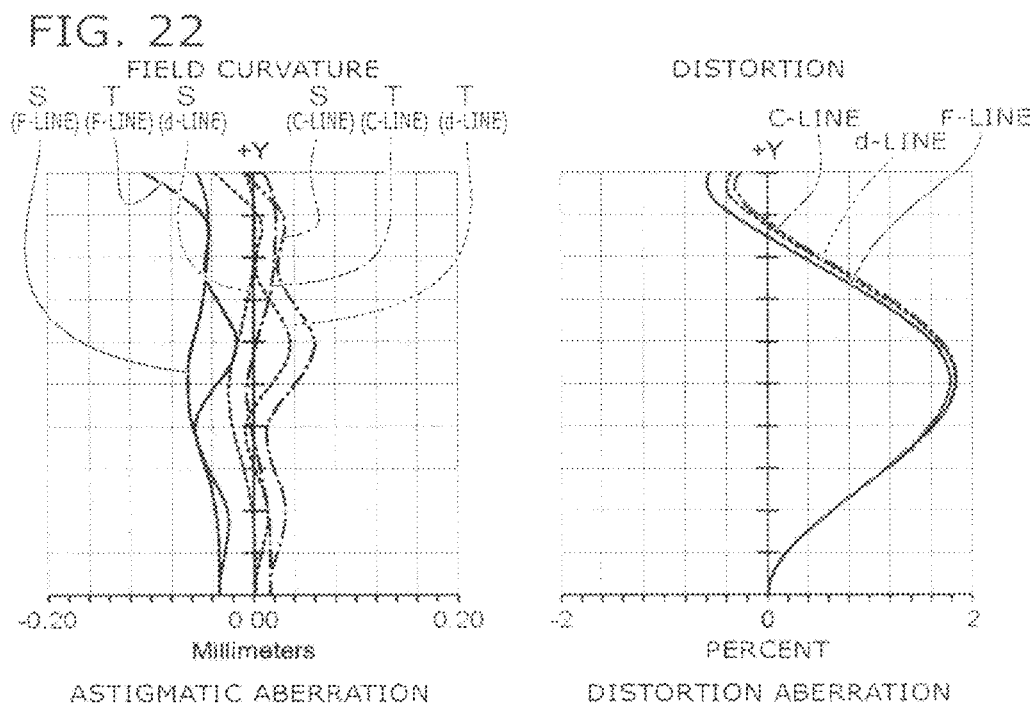
S   L1   L2   L3

12

CG

MLA
(14)

DT
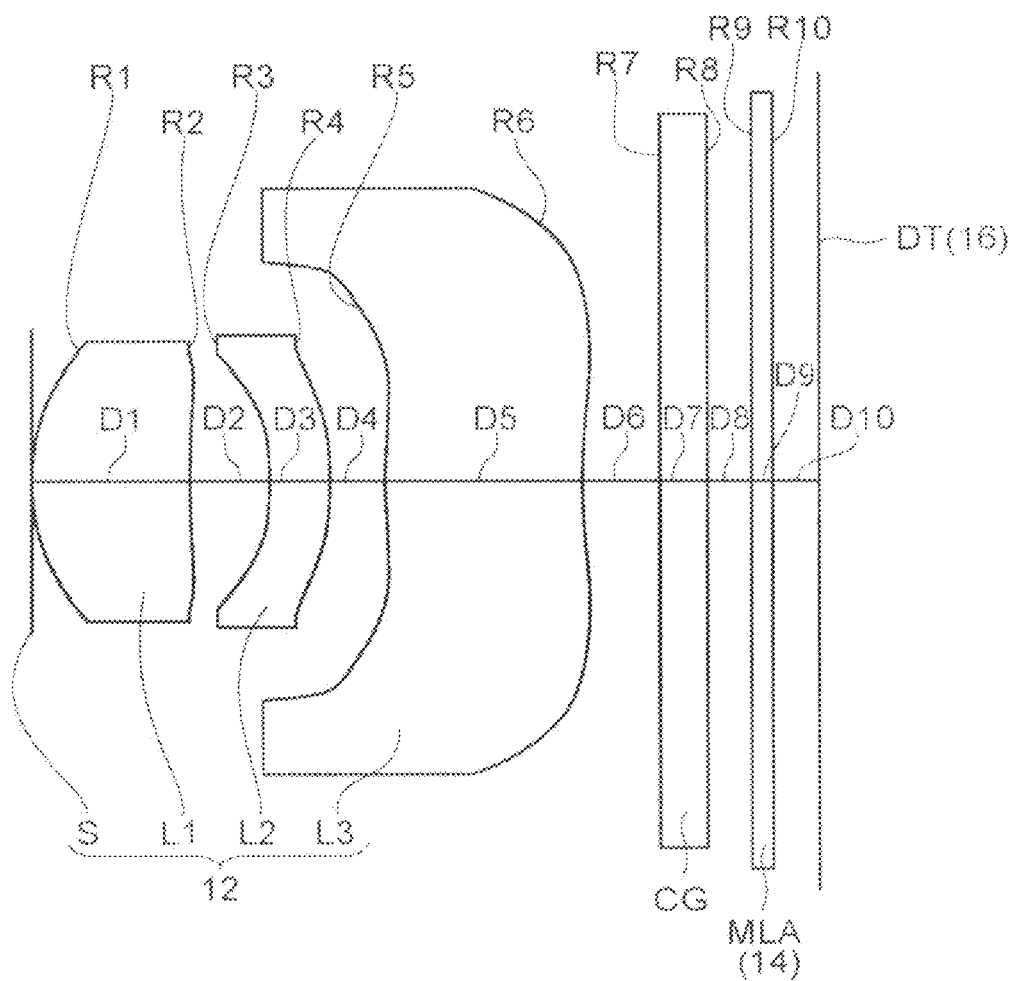
FIG. 33

LIGHT RAY X MINIMUM =−1.3061   LIGHT RAY X MAXIMUM =1.3061
LIGHT RAY Y MINIMUM =−1.4657   LIGHT RAY Y MAXIMUM =0.7228

- $a=1.3061$ $b=(0.7228+1.4657)/2 =1.09425$
- $\rho = |1- 1.09425/1.3061| = 0.162$

FIG. 34

FIG. 35

FIG. 36

F2.19

F-LINE   d-LINE   C-LINE

-0.1   -0.08   -0.06   -0.04   -0.02   0   0.02   0.04   0.06   0.08   0.1

Millimeters

SPHERICAL ABERRATION

FIG. 37

FIELD CURVATURE

S   T   S   S   T   T
(F-LINE) (F-LINE) (d-LINE)   (C-LINE) (C-LINE) (d-LINE)

+Y

-0.20   0.00   0.20

Millimeters

ASTIGMATIC ABERRATION

DISTORTION

F-LINE   d-LINE   C-LINE

+Y

-1   0   1

PERCENT

DISTORTION ABERRATION

EXIT PUPIL POSITION
(OFF-AXIS HALF-ANGLE OF VIEW ω = 32.15 DEGREES)
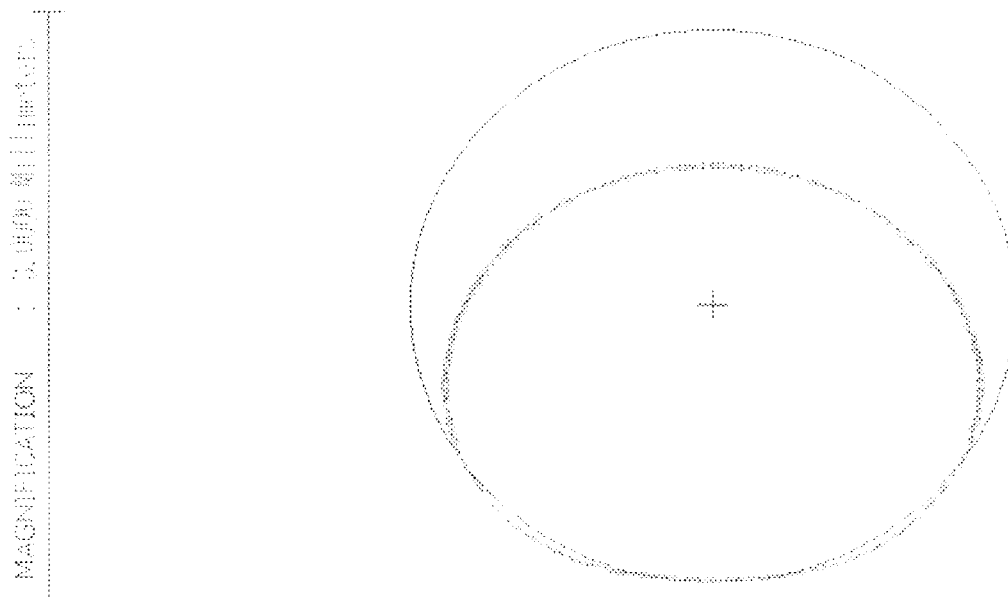
DT

S   L1   L2   L3

12

CG

MLA
(14)

FIG. 38

LIGHT RAY X MINIMUM=-1.3621   LIGHT RAY X MAXIMUM=1.3621

LIGHT RAY Y MINIMUM=-1.5788   LIGHT RAY Y MAXIMUM=0.7192

* a=1.3621   b=(0.7192+1.5788)/2 = 1.149

* ρ = | 1- 1.149/1.3621 | = 0.1564

FIG. 39

IMAGING LENS AND SOLID STATE IMAGING DEVICE

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is based upon and claims the benefit of priority from Japanese Patent Application No. 2013-193518, filed on Sep. 18, 2013; the entire contents of which are incorporated herein by reference.

FIELD

Embodiments described herein relate generally to an imaging lens and a solid state imaging device.

BACKGROUND

Various methods are being used as imaging technology that can obtain lengths in the depth direction of a subject as two-dimensional information (a range image) such as technology that uses a reference beam to measure the reflected light intensity and/or return time fro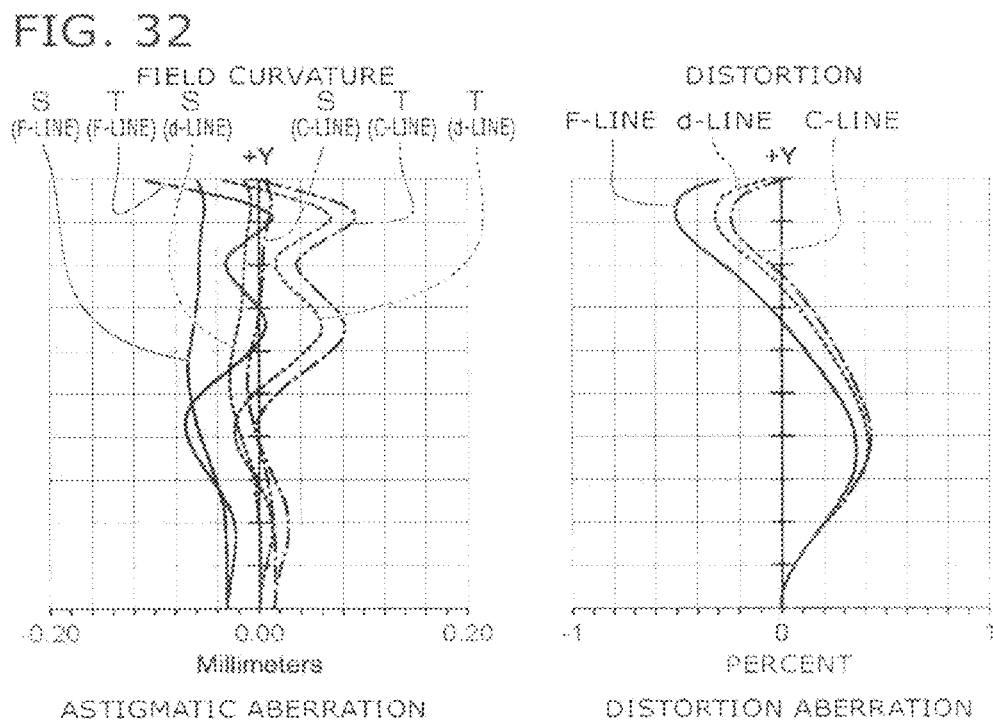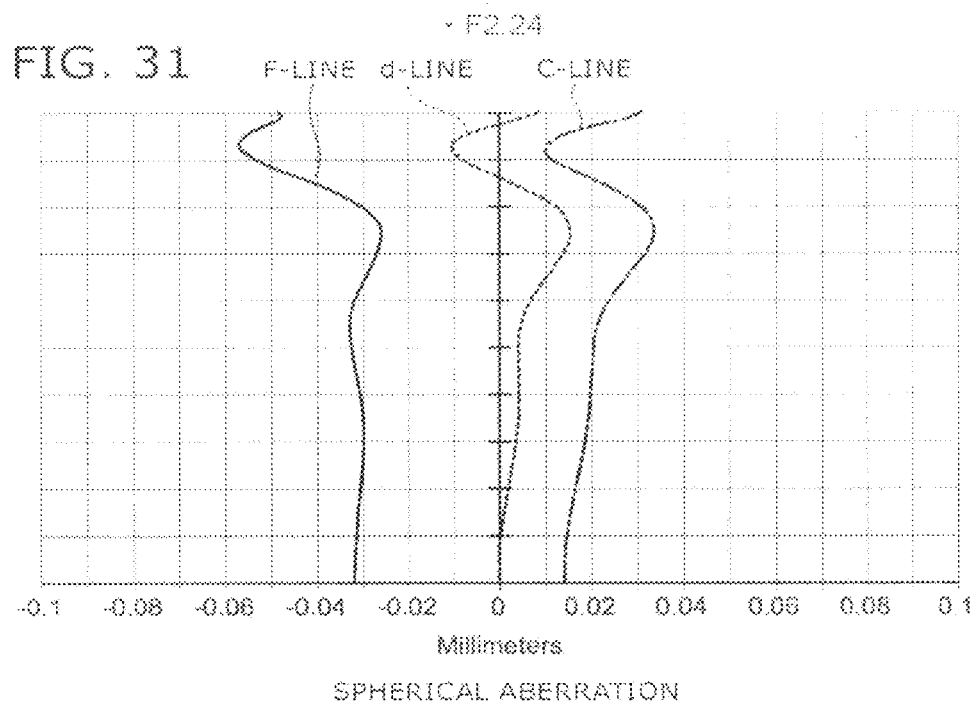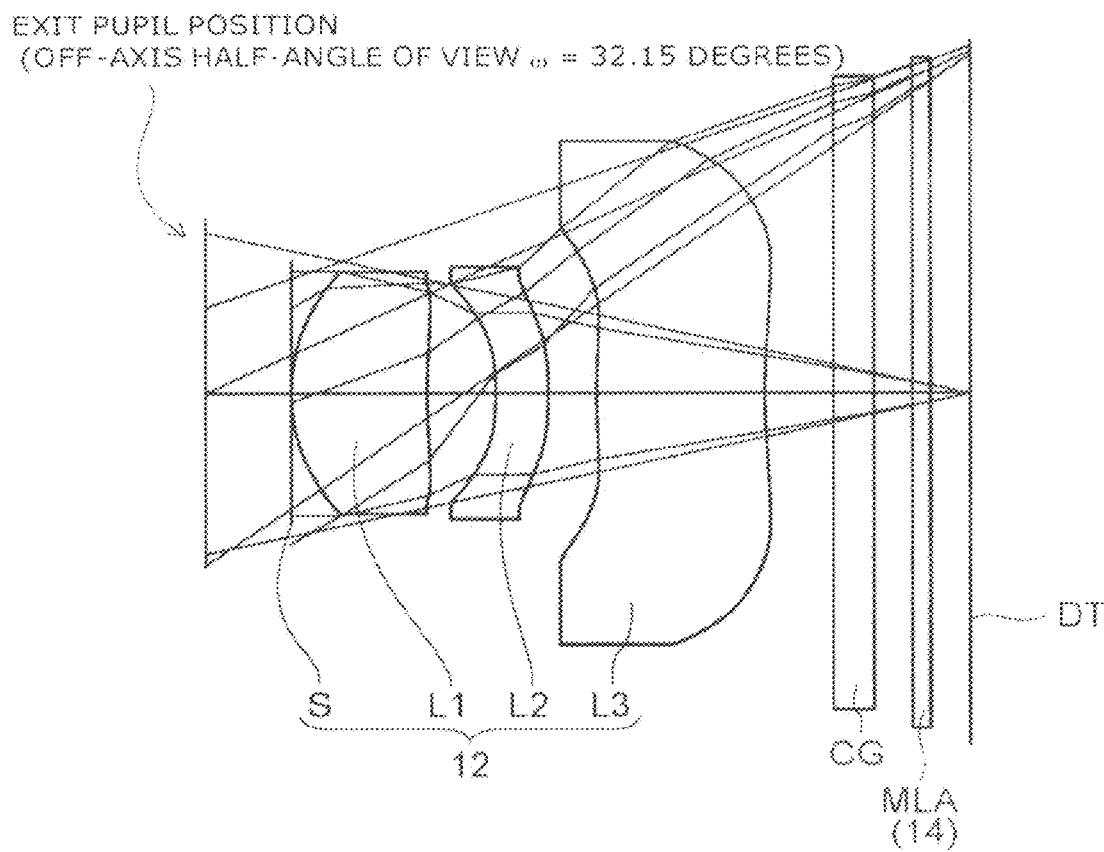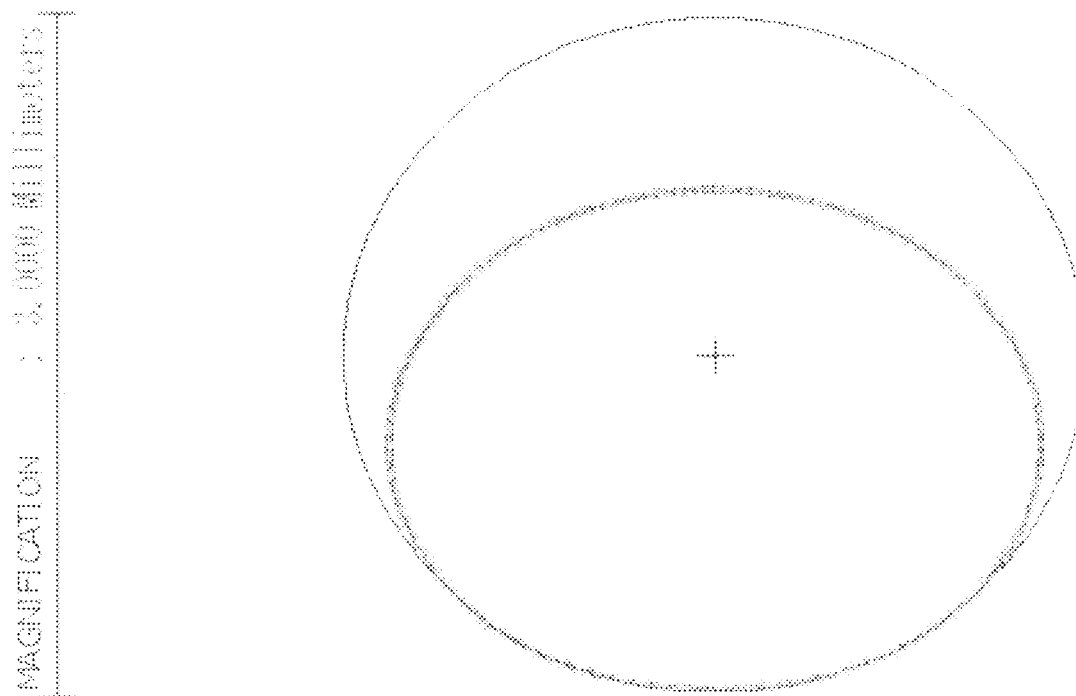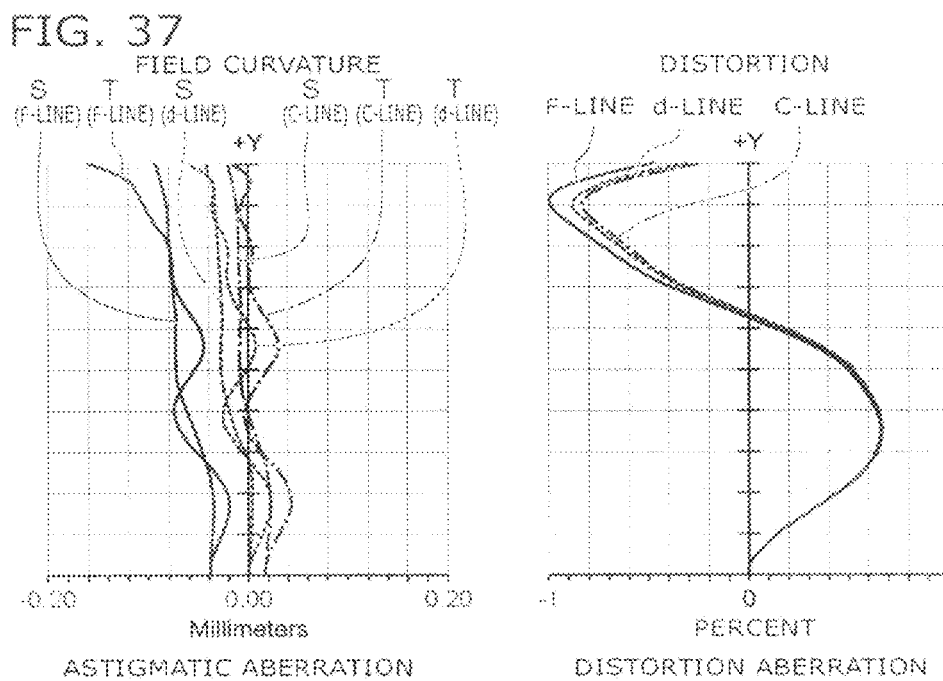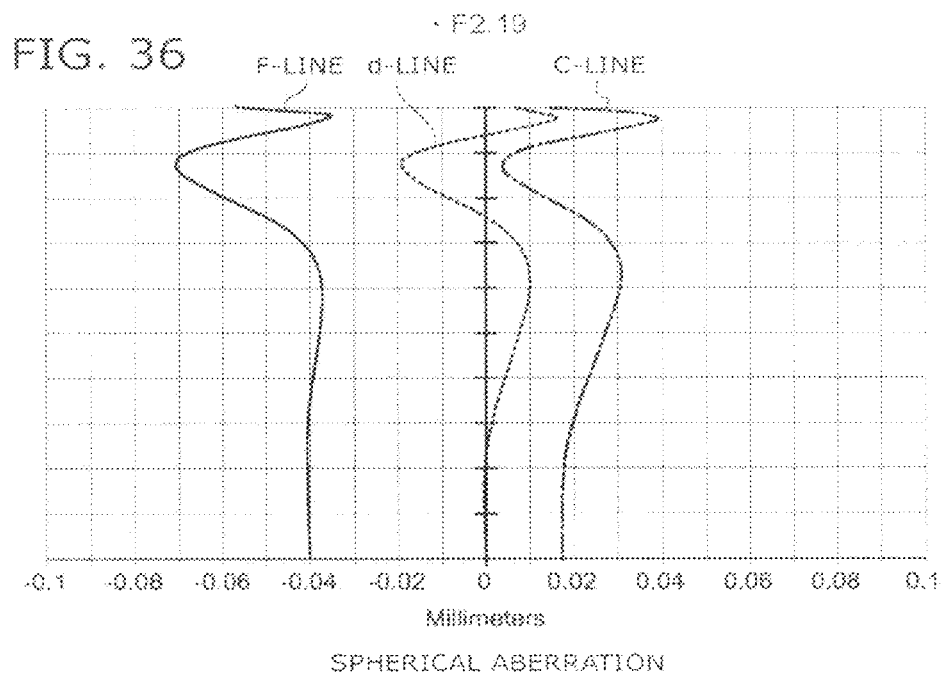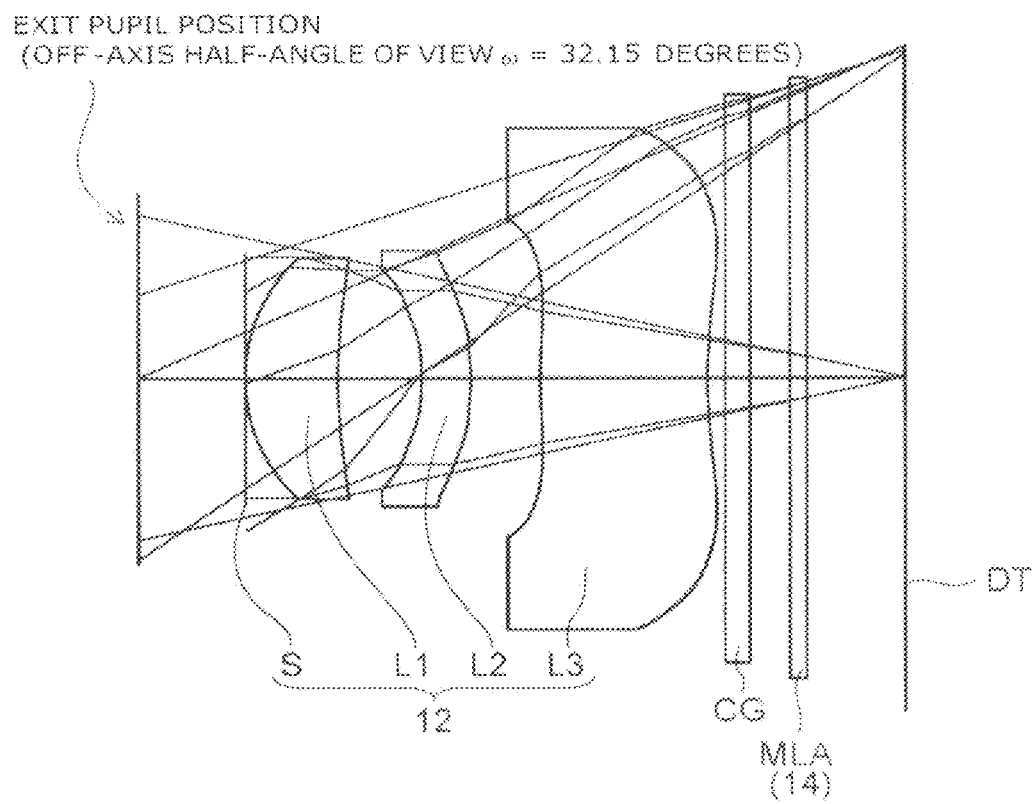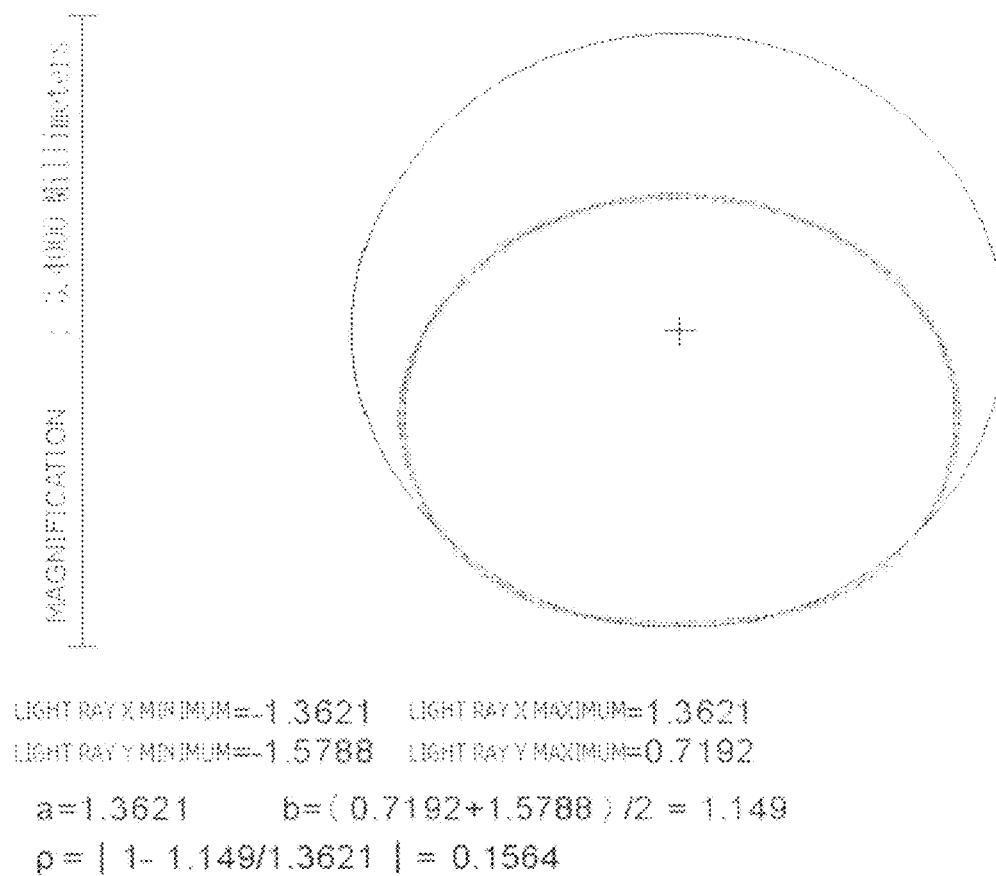m the subject, stereoscopic ranging technology using multiple cameras, etc. Better subject recognition is possible by using range image information than by using the image information obtained from a normal camera. Therefore, the demand is increasing for applications of range image information as new input information in relatively inexpensive products for appliances, games, industrial applications, etc.

Among distance imaging methods, a solid state imaging device that includes an imaging optical system and multiple optical systems has been proposed as a configuration in which a single camera is used to obtain many sets of parallax and the ranging is performed based on triangulation. In such a solid state imaging device, multiple optical systems are disposed as a re-imaging optical system between the imaging optical system and the imaging element. For example, a microlens array in which many microlenses are formed on a plane is used as the multiple optical systems.

Multiple pixels are disposed under each of the microlenses. The images that are demagnified by the imaging optical systems are imaged on the imaging element by the microlens array. The simple-eye images that are imaged have viewpoints shifted by the amount of parallax existing due to the arrangement position of each microlens.

The distance estimation of the subject is possible using the principle of triangulation by performing signal processing of the images of the parallax image groups obtained from many microlenses. Further, it is possible to reconstruct the images as a two-dimensional image by performing image processing to link the images together.

In an imaging lens and a solid state imaging device, it is desirable to acquire both a high-precision range image and a good visible image.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram illustrating a solid state imaging device according to the embodiment;

FIG. 2 is a schematic cross-sectional view illustrating the solid state imaging device according to the embodiment;

FIG. 3A and FIG. 3B illustrate the relationship between groups of light rays and the distance from the subject to the imaging lens;

FIG. 4 illustrates the geometrical optical relationship of the microlenses at the optical-axis center of the imaging lens;

FIG. 5A to FIG. 5C illustrate the overlapping field of view relationship of the microlenses;

FIG. 6A to FIG. 6E illustrate the method for reconstructing the two-dimensional image;

FIG. 7 illustrates the arithmetic average;

FIG. 8 shows the heights of light rays passing through the lens cross sections;

FIG. 9 shows the flattening of the exit pupil;

FIG. 10 illustrates the configuration of the imaging lens according to the embodiment;

FIG. 11 is a schematic plan view illustrating the arrangement of the microlens units;

FIG. 12 is a ray diagrams of the microlenses;

FIG. 13 is a ray diagrams of the microlenses;

FIG. 14 is a ray diagram of a microlens;

FIG. 15 shows aberration curves of the microlens;

FIG. 16 is a ray diagram of the microlens;

FIG. 17 shows aberration curves of the microlens;

FIG. 18 is a ray diagram of the microlens;

FIG. 19 shows aberration curves of the microlens;

FIG. 20 illustrates the configuration of an imaging lens according to a first example;

FIG. 21 is various aberration diagrams of the imaging lens according to the first example;

FIG. 22 is various aberration diagrams of the imaging lens according to the first example;

FIG. 23 illustrates the exit pupil position of the imaging lens according to the first example;

FIG. 24 illustrates the configurations and numerical values of the exit pupils of the imaging lens according to the first example;

FIG. 25 illustrates the configuration of an imaging lens according to a second example;

FIG. 26 is various aberration diagrams of the imaging lens according to the second example;

FIG. 27 is various aberration diagrams of the imaging lens according to the second example;

FIG. 28 illustrates the exit pupil position of the imaging lens according to the second example;

FIG. 29 illustrates the configurations and numerical values of the exit pupils of the imaging lens according to the second example;

FIG. 30 illustrates the configuration of an imaging lens according to a third example;

FIG. 31 is various aberration diagrams of the imaging lens according to the third example;

FIG. 32 is various aberration diagrams of the imaging lens according to the third example;

FIG. 33 illustrates the exit pupil position of the imaging lens according to the third example;

FIG. 34 illustrates the configurations and numerical values of the exit pupils of the imaging lens according to the third example;

FIG. 35 illustrates the configuration of an imaging lens according to a fourth example;

FIG. 36 is various aberration diagrams of the imaging lens according to the fourth example;

FIG. 37 is various aberration diagrams of the imaging lens according to the fourth example;

FIG. 38 illustrates the exit pupil position of the imaging lens according to the fourth example; and

FIG. 39 illustrates the configurations and numerical values of the exit pupils of the imaging lens according to the fourth example.

DETAILED DESCRIPTION

According to one embodiment, an imaging lens includes a first optical system and a microlens array. The first optical

system includes an optical axis. The microlens array is provided between the first optical system and an imaging element. The microlens array includes a plurality of microlens units provided in a first plane. The imaging element includes a plurality of pixel groups. Each of the pixel groups includes a plurality of pixels. The microlens units respectively overlap the pixel groups when projected onto the first plane. The first optical system includes an aperture stop, a first lens, a second lens, and a third lens. The first lens is provided between the aperture stop and the microlens array, and has a positive refractive power. The first lens has a first surface, and a second surface, the first surface opposing the aperture stop, the second surface being provided between the first surface and the microlens array. The second lens is provided between the first lens and the microlens array, and has a negative refractive power. The second lens has a third surface, and a fourth surface, the third surface opposing the second surface, the fourth surface being provided between the third surface and the microlens array. The third lens is provided between the second lens and the microlens array, and has a positive refractive power. The third lens has a fifth surface, and a sixth surface, the fifth surface opposing the fourth surface, the sixth surface being provided between the fifth surface and the microlens array. A curvature radius of the first surface is positive. A curvature radius of the third surface and a curvature radius of the fourth surface are negative. A curvature radius of the fifth surface and a curvature radius of the sixth surface are positive. At least one selected from the first to sixth surfaces has an aspherical configuration. Formulas (1) to (6) are satisfied, where f is a focal length of the first optical system, f1 is a focal length of the first lens, f2 is a focal length of the second lens, f3 is a focal length of the third lens, TL is a distance between the aperture stop and the imaging element, D2 is a distance along the optical axis between the second lens and the third lens, and D5 is a thickness along the optical axis of the third lens:

$$0.6 < f1/f < 0.9 \tag{1}$$

$$1.0 < |f2|/f < 3.0 \tag{2}$$

$$2.0 < f3/f < 200 \tag{3}$$

$$f/TL < 1.3 \tag{4}$$

$$0 < D2/f < 0.2 \tag{5}$$

$$0 < D5/f < 0.5 \tag{6}.$$

Various embodiments will be described hereinafter with reference to the accompanying drawings. In the description hereinbelow, similar members are marked with like reference numerals, and a description is omitted as appropriate for members once described.

Configuration of Camera Module

FIG. 1 is a block diagram illustrating a solid state imaging device according to the embodiment.

The solid state imaging device 1 shown in FIG. 1 is, for example, a camera module.

As shown in FIG. 1, the solid state imaging device 1 includes an imaging module unit 10 and an imaging signal processor (hereinbelow, also called an ISP (Image Signal Processor)) 20.

The imaging module unit 10 includes an imaging optical system (a first optical system) 12, a microlens array 14 (hereinbelow, also called the MLA (Micro Lens Array)), an imaging element (a solid-state imaging element 16), and an imaging circuit 18.

The imaging optical system 12 functions as an imaging optical system that guides the light from the subject onto the solid-state imaging element 16. The solid-state imaging element 16 functions as an element that converts the light guided by the imaging optical system 12 into a signal charge. Multiple pixels (e.g., photodiodes used as photoelectric conversion elements) are arranged in a two-dimensional array configuration along the light reception surface.

The microlens array 14 includes, for example, multiple microlens units 14a. The microlens units 14a may be micro-optical systems such as prisms, etc. The individual microlens units 14a of the microlens array 14 demagnify the group of light rays that is imaged at the imaging plane (the virtual imaging plane) by the imaging optical system 12. The image that is demagnified by each of the microlens units 14a is imaged on a pixel block (a group of multiple pixels) corresponding to the microlens unit 14a.

The imaging circuit 18 includes a drive circuit unit (not shown) that drives the pixels of the pixel array of the solid-state imaging element 16, and a pixel signal processing circuit unit (not shown) that processes the signals output from the pixel region.

The drive circuit unit includes, for example, a vertical selection circuit that sequentially selects the pixels to be driven in the vertical direction by horizontal line (row) units, a horizontal selection circuit that sequentially selects the pixels to be driven by column units, and a TG (a timing generator) circuit that drives the vertical selection circuit and the horizontal selection circuit by various pulses.

The pixel signal processing circuit unit includes an AD conversion circuit that performs digital conversion of the analog electrical signals from the pixel region, a gain control/amplifier circuit that performs gain control and/or amplifier operations, and a digital signal processing circuit that performs correction processing of the digital signals, etc.

The ISP 20 includes a camera module I/F (an interface) 22, an image acquisition unit 24, a signal processing unit 26, and a driver I/F 28. The image acquisition unit 24 acquires, from the camera module I/F 22, the raw image obtained by the imaging by the imaging module unit 10.

The signal processing unit 26 implements signal processing of the raw image acquired by the image acquisition unit 24. The driver I/F (the interface) 28 outputs the image signal that has undergone the signal processing of the signal processing unit 26 to a not-shown display driver. The display driver displays the image that is imaged by the solid state imaging device 1.

Member Configuration of Camera Module

FIG. 2 is a schematic cross-sectional view illustrating the solid state imaging device according to the embodiment.

In the solid state imaging device 1 according to the embodiment as shown in FIG. 2, the solid-state imaging element 16 is formed in a semiconductor substrate 16a. The solid-state imaging element 16 includes multiple pixel groups 16e. Each of the multiple pixel groups 16e includes multiple pixels 16b. The multiple pixels 16b include photodiodes and are provided on the semiconductor substrate 16a. The pitch (the pixel pitch) between the mutually-adjacent pixels 16b is, for example, not less than about 0.7 micrometers (μm) and not more than about 2.7 μm. The size of the solid-state imaging element 16 is, for example, not less than about 3.0 millimeters (mm) and not more than about 6.0 mm in the longitudinal direction and not less than about 4.0 mm and not more than about 8.0 mm in the lateral direction. The volume of the entire solid state imaging device 1 is, for example, about 1 cubic centimeter (cm³).

A drive/read-out circuit (not shown) that drives the pixels **16***b* and reads the signals from the pixel **16***b* is formed on the semiconductor substrate **16***a*.

On each of the multiple pixels **16***b*, a color filter **16***c* of R (having a high transmittance for light of the red wavelength light region), G (having a high transmittance for light of the green wavelength light region), B (having a high transmittance for light of the blue wavelength light region), or W (transmitting red, green, and blue wavelength light) is formed for every pixel **16***b*. A pixel concentrating microlens **16***d* may be formed at the upper portion of the color filter **16***c* every one pixel **16***b*.

The microlens array **14** is disposed on the color filter **16***c*. The microlens array **14** includes a visible light-transmissive substrate **14***b*, and the microlens units **14***a* formed on the visible light-transmissive substrate **14***b*. The microlens units **14***a* are disposed on the solid-state imaging element **16** side as viewed from the visible light-transmissive substrate **14***b*. The multiple microlens units **14***a* are provided in a first plane **14***p*. The multiple microlens units **14***a* are arranged in a two-dimensional array configuration on the visible light-transmissive substrate **14***b*. The microlens units **14***a* are provided to correspond to the pixel blocks made of the multiple pixels **16***b* provided on the semiconductor substrate **16***a*. In other words, the multiple microlens units **14***a* respectively overlap the multiple pixel groups **16***e* when projected onto the first plane **14***p*. Each of the microlens units **14***a* functions as an optical system that performs demagnification and imaging onto the corresponding pixel block.

The visible light-transmissive substrate **14***b* is provided to be separated from the solid-state imaging element **16**. A spacer **42** that includes a resin material, etc., is provided between the visible light-transmissive substrate **14***b* and the semiconductor substrate **16***a* in which the solid-state imaging element **16** is formed. The visible light-transmissive substrate **14***b* is bonded to the semiconductor substrate **16***a* via the spacer **42**. The alignment when bonding the semiconductor substrate **16***a* and the visible light-transmissive substrate **14***b* is performed using an alignment mark, etc., as a reference.

The visible light-transmissive substrate **14***b* may be a material that not only transmits visible light but also cuts, for example, unnecessary near-infrared light. A multilayered film or a single-layer film that transmits visible light and reflects near-infrared light may be formed in the visible light-transmissive substrate **14***b*.

Also, an optical filter **43** is provided at the upper portion of the visible light-transmissive substrate **14***b* as necessary. In the example, the optical filter **43** is provided between the imaging optical system **12** and the microlens array **14**. In the case where the visible light-transmissive substrate **14***b* does not function to cut near-infrared light, the optical filter **43** that has a similar function is disposed separately.

Further, an electrode pad **44** for reading the pixels **16***b* is provided in the semiconductor substrate **16***a*. A vertical electrical connection **46** that is electrically connected to a processing and driver chip is made in the lower portion of the electrode pad **44** to pierce the semiconductor substrate **16***a*.

The semiconductor substrate **16***a* is electrically connected to the processing and driver chip **50** via the vertical electrical connection **46** and a bump **48**. The drive processing circuit (the imaging circuit **18**) that drives the solid-state imaging element **16** and processes the signals that are read is formed in the processing and driver chip **50**. The electrical connection between the semiconductor substrate **16***a* and the processing and driver chip **50** is not limited to the vertical electrical

connection **46**; and the electrical connection may be made by a metal wire, etc., between electrode pads provided on the two chips.

The imaging optical system **12** is provided above the visible light-transmissive substrate **14***b*. The imaging optical system **12** includes multiple lenses. The imaging optical system **12** is mounted to a lens optical column **62**. The lens optical column **62** is mounted to a lens holder **64**. Due to the relationship between the insertion pressure and the output image, the mounting position of the imaging optical system **12** may be adjusted when mounting the lens holder **64**.

A light-shielding cover **52** that shields unnecessary light is mounted around the semiconductor substrate **16***a*, the visible light-transmissive substrate **14***b*, and the processing and driver chip **50**. A module electrode **54** that electrically connects the processing and driver chip **50** to the outside is provided in the lower portion of the processing and driver chip **50**.

Microlens Geometrical Optical Relationship Diagram

The geometrical optical relationship of the optical system (the virtual image optical system) of the solid state imaging device **1** of the embodiment will now be described.

FIG. **3A** and FIG. **3B** illustrate the relationship between groups of light rays and the distance from the subject to the imaging lens.

FIG. **4** illustrates the geometrical optical relationship of the microlenses at the optical-axis center of the imaging lens.

FIG. **5A** to FIG. **5C** illustrate the overlapping field of view relationship of the microlenses.

The imaging optical system **12** has an optical axis Ox. In the description hereinbelow, only the area proximal to the optical axis of the lenses of the imaging optical system **12** is described for simplification.

When considering only the imaging optical system **12**, a chief ray from a subject point P on the optical axis and peripheral rays which are from the same family of light rays as the chief ray are imaged at a virtual imaging plane **70** which is determined by the focal length f of the imaging optical system and a distance A between the imaging optical system **12** and the subject point **100**P so that the relationship of Formula 1 is satisfied.

$$\frac{1}{f} = \frac{1}{A} + \frac{1}{B} \qquad \text{[Formula 1]}$$

Here, f is the focal length of the imaging optical system **12**, A is the distance from an object-side principal plane **12***a* of the imaging optical system **12** to the subject point **100**P, and B is the distance from an image-side principal plane **12***a* of the imaging optical system **12** to a virtual imaging point P'**70**. The image magnification (the horizontal magnification) of the imaging optical system **12** expressed by Formula 2 recited below.

$$M = \frac{B}{A} \qquad \text{[Formula 2]}$$

Here, in the embodiment, the virtual imaging point P'**70** of the imaging optical system **12** is positioned rearward (on the side opposite to the subject **100**) of the solid-state imaging element **16**. In other words, the solid-state imaging element **16** is provided between the virtual imaging point P'**70** and the imaging optical system **12**. For example, the virtual imaging point P'**70** is a point that is positioned at the focal length f from

7

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the imaging optical system **12**. In such a case, because the microlens units **14a** are disposed frontward of the virtual imaging point P'**70**, the light is concentrated onto the surface of the solid-state imaging element **16** that includes the pixels and is positioned frontward of the virtual imaging plane **70**. In such a case, groups of light rays **80** and **82** are demagnified and imaged with a virtual image relationship. The optical imaging system of the microlens units **14a** is expressed by Formula 3 recited below.

$$\frac{1}{g} = -\frac{1}{C} + \frac{1}{D} \qquad \text{[Formula 3]}$$

Here, g is the focal length of the microlens units **14a**, C is the distance from the object-side principal plane of the microlens units **14a** to the virtual imaging point P'**70**, and D is the distance from the image-side principal plane of the microlens units **14a** to the optical imaging points of the microlenses. In such a case, the image magnification due to the optical imaging system of the microlens units **14a** is expressed by Formula 4 recited below.

$$N = \frac{D}{C} \qquad \text{[Formula 4]}$$

Here, variable E of Formula 5 recited below is introduced from the geometrical optical relationship. Variable E is a fixed design value in the case where the optical system is a fixed focus optical system.

$$E = B - C \qquad \text{[Formula 5]}$$

Here, for two adjacent microlens units **14a**, L_{ML} is the arrangement pitch of the microlens units **14a** or the distance between the microlens units **14a**. In such a case, groups of light rays **84a**, **84b**, **84c**, and **86** that are emitted from the same subject are distributed by adjacent multiple microlens units **14a** to be imaged on the multiple locations of image points p1, p2, p3, ... Here, L_{ML} and an image shift length ˆ on one side are expressed by Formula 6 recited below from the geometrical optical relationship of the chief rays **84a**, **84b**, and **84c** for each of the microlens units **14a** shown in FIG. **4**.

$$\frac{C}{L_{ML}} = \frac{D}{\Delta} \qquad \text{[Formula 6]}$$

From Formula 1, Formula 2, and Formula 6, the shift length Δ of the image and the distance A from the imaging optical system **12** to the subject have the relationship shown in Formula 7 recited below.

$$A = \left(\frac{1}{f} - \frac{1}{B}\right)^{-1} = \left(\frac{1}{f} - \frac{1}{E+C}\right)^{-1} = \left(\frac{1}{f} - \frac{1}{E + \dfrac{DL_{ML}}{\Delta}}\right)^{-1} \qquad \text{[Formula 7]}$$

In Formula 7, f, E, and L_{ML} are parameters of design and are known fixed values; and Δ and D are determined uniquely from A.

Here, D can be taken to be a fixed value D0 because the change amount of D is extremely small compared to the change amount of A. D0 is the distance from the image-side principal plane of the microlens units **14a** to the surface of the

solid-state imaging element **16**. In such a case, Formula 7 is expressed as Formula 8 recited below.

$$A = \left(\frac{1}{f} - \frac{1}{B}\right)^{-1} = \left(\frac{1}{f} - \frac{1}{E+C}\right)^{-1} = \left(\frac{1}{f} - \frac{1}{E + \dfrac{D_0 L_{ML}}{\Delta}}\right)^{-1} \qquad \text{[Formula 8]}$$

Here, because f, E, D0, and L_{ML} are design values and are known, the subject distance A is calculatable if the shift length Δ of the image can be sensed from the imaging element surface.

Image matching between the images of adjacent microlenses recorded by the imaging element is used to determine the shift length Δ between the images when using the imaging lens and the microlenses to image the light rays emitted from one subject point P at p1, p2, p3, ...

For the image matching, a well-known template matching method that examines, for example, the degree of similarity and/or the degree of dissimilarity between two images can be used. Further, when determining the shift position more precisely, the shift length can be determined more precisely by interpolating the degree of similarity and/or the degree of dissimilarity obtained for each pixel unit using a continuous fitting function, etc., and determining the subpixel positions where the fitting function is a maximum and a minimum.

Method for Reconstructing Two-Dimensional Image

A method for reconstructing a two-dimensional image without overlap from the microlens image groups when the same subject is multiply imaged will now be described with reference to FIG. **5A** to FIG. **5C**.

The case is considered where there are three adjacent microlens units **14a**; and the three adjacent microlens units **14a** respectively form microlens images **91a**, **91b**, and **91c** at the surface of the solid-state imaging element **16** as shown in FIG. **5B**.

Thus, to form the microlens images without overlap, it is sufficient for the F-number of the imaging optical system **12** and the F-number of the microlenses to match.

A field of view **93a**, a field of view **93b**, and a field of view **93c** at the virtual imaging plane **70** are the fields of view where the images **91a**, **91b**, and **91c** of the microlenses are imaged and are areas that overlap as shown in FIG. **5C**. FIG. **5B** and FIG. **5C** show the case where an image demagnification ratio N is 0.5; and each field of view is multiplied by 0.5 to be imaged with a relationship such that each subject point overlaps two or more times. For the relationship N=0.5, the image at the virtual imaging plane **70** can be reproduced by multiplying each microlens image by 1/N, i.e., by 2.

The image demagnification ratio N can be known from the microlens image group after the imaging because Formula 9 recited below can be derived from the relationship of Formula 4 and Formula 6.

$$N = \frac{D}{C} = \frac{\Delta}{L_{ML}} \qquad \text{[Formula 9]}$$

Because the pitch L_{ML} of the microlenses is known, the image demagnification ratio N can be determined by determining the shift length Δ of the same subject from the images. The pitch L_{ML} is, for example, not less than about 10 μm and not more than about 60 μm.

Synthesizing Method for Reconstructing Two-Dimensional Image

The image synthesizing method for reconstructing the two-dimensional image will now be described.

FIG. **6A** to FIG. **6E** illustrate the method for reconstructing the two-dimensional image.

FIG. **6A** shows a flowchart of the image synthesizing method. FIG. **6B** shows an example of a plenoptic image; FIG. **6C** shows an enlargement and arithmetic average example of the pixel signals; FIG. **6D** shows an example of the pixel correspondence of the signals of the pixels; and FIG. **6E** shows an example of the two-dimensional image.

First, as shown in FIG. **6A**, the output of the plenoptic image (referring to FIG. **6B**) from the imaging element is obtained (step S**101**). The plenoptic image is, for example, a raw image. The plenoptic image includes multiple picture cells (pixels); and each of the multiple pixels corresponds to one selected from mutually-different multiple colors (e.g., red, green, and blue). Then, white balance processing of the plenoptic raw image output from the imaging element is performed to adjust the signal balance of B (blue), G (green), and R (red) (step S**102**). In other words, the white balance processing adjusts the signal balance between the multiple colors.

Continuing, for example, because there is no G and B signal information at the position of the R pixels, demosaicing is performed to make the G and B signals by estimating the G and B signals by referring to the pixels disposed around the R pixels (step S**103**). In other words, for example, the multiple pixels include a first pixel (a first picture cell) corresponding to a first color (e.g., red). The demosaicing estimates the signal of a second color (e.g., green or blue) of the first pixel by referring to the pixels of the multiple pixels disposed around the first pixel. Although it is sufficient to simply perform processing to find the average from the surroundings pixels, various methods are possible as necessary such as widening the pixel area that is referred to, etc. (referring to FIG. **6C**). The demosaicing is performed similarly for the G pixels and the B pixels.

Continuing, the image points p1, p2, . . . , pn that correspond to one subject point P (a first point) such as that shown in FIG. **6D** have an n-to-1 correspondence with a signal S'_p after the synthesis of the pixel signal values $S_{p1}, S_{p2}, \ldots, S_{pn}$ recorded by the imaging element (step S**104**). That is, the plenoptic image includes the multiple image points p1, p2, . . . , pn corresponding to the subject point P of the subject. The correspondence between the first point and each of the multiple image points p1, p2, . . . , pn is calculated in step S**104**. The correspondence method is performed by sensing the relationship of the image point shift length Δ or the overlap relationship of the fields of view from the image as described above.

Subsequently, two-dimensional image synthesis is performed (step S**105**); the two-dimensional image (referring to FIG. **6E**) is obtained; and the flow ends. For example, the pixel values of the multiple image points p1, p2, . . . , pn are synthesized based on the correspondence calculated in step S**104**. Thereby, a post-synthesis signal corresponding to the subject point P is calculated. Thus, the two-dimensional image is calculated.

The two-dimensional image synthesis will now be described.

FIG. **7** illustrates the arithmetic average.

Here, the pixel signal values $S_{p1}, S_{p2}, \ldots, S_{pn}$ and noise values $N_{p1}, N_{p2}, \ldots, N_{pn}$ of the pixels are used in the description. First, luminance correction processing of each pixel signal value and noise value is performed. Then, lumi-

nance correction coefficients $a_1, a_2, \ldots, a_n$ are multiplied respectively by the pixel signal values $S_{p1}, S_{p2}, \ldots, S_{pn}$.

Continuing, the post-synthesis signal value S'_p is calculated by the arithmetic average of the values after the multiplications as shown in Formula 10 recited below. Also, the noise value included in the post-synthesis signal value at this time is as shown in Formula 11.

$$S'_p = (a_1 \cdot S_{p1} + a_2 \cdot S_{p2} + \ldots + a_n \cdot S_{pn})/n \qquad \text{[Formula 10]}$$

$$N'_p = (a_1^2 \cdot n_{p1}^2 + a_2^2 \cdot n_{p2}^2 + \ldots a_n^2 \cdot n_{pn}^2)^{0.5}/n \qquad \text{[Formula 11]}$$

Relationship between ranging performance and configuration of exit pupil

FIG. **8** shows the heights of light rays passing through the lens cross sections.

FIG. **9** shows the flattening of the exit pupil.

As shown in FIG. **8**, the imaging optical system **12** includes the aperture stop S, a first lens L**1**, a second lens L**2**, and a third lens L**3**. The first lens L**1** is provided between the aperture stop S and the microlens array **14**. The second lens L**2** is provided between the first lens L**1** and the microlens array **14**. The third lens L**3** is provided between the second lens L**2** and the microlens array **14**.

The lens group that includes the first lens L**1**, the second lens L**2**, and the third lens L**3** is the main lens. As shown in FIG. **8**, in the case where a virtual plane **12***p* is disposed in the space between the second lens L**2** and the third lens L**3** through which off-axis light rays passes, the following definitions are made for the light rays that pass through the virtual plane.

For example, off-axis light rays that travel in a direction intersecting the optical axis Ox are considered. Off-axis light rays L**23** include an upper light ray L**23***u*, a lower light ray L**23***d*, and a chief ray L**23***m*. The lower light ray L**23***d* is positioned between the upper light ray L**23***u* and the optical axis Ox at the virtual plane. The chief ray L**23***m* is positioned between the upper light ray L**23***u* and the lower light ray L**23***d* at the virtual plane.

h(G23iCR) is the height at which the chief ray L**23***m* of the off-axis light rays passes through the virtual plane.

h(G23iUR) is the height at which the upper light ray L**23***u* of the off-axis light rays passes through the virtual plane.

h(G23iDW) is the height at which the lower light ray L**23***d* of the off-axis light rays passes through the virtual plane.

The following definitions are made for the chief ray of the off-axis light rays propagating into the page surface.

hx(G23iURX) is the length in the depth direction where the light ray inside the perpendicular plane (passing through the sagittal plane) passes through the virtual plane.

The configuration of an exit pupil EP shown in FIG. **9** is the configuration at the virtual plane of the off-axis light rays. The configuration of the exit pupil EP is, for example, treated as an ellipse. In such a case, the configuration of the exit pupil EP has a first diameter and a second diameter. The first diameter is the diameter along a first direction (the X-direction) in the virtual plane of the exit pupil EP. The second diameter is the diameter along a second direction (the Y-direction) in the virtual plane of the exit pupil EP. The following definitions are made for the flattening of the exit pupil EP.

½ times the first diameter is a. In the case where the exit pupil EP is treated as substantially a circle or an ellipse, the first diameter is the major diameter of the length of the pupil at the exit pupil position; and a=hx(G23iURX).

½ times the second diameter is b. In the case where the exit pupil EP is treated as substantially a circle or an ellipse, the

second diameter is the minor diameter of the length of the pupil at the exit pupil position; and b=(hy(G23iUR)−hy (G23iDW))/2.

Flattening p is defined as $\rho = |1 - b/a|$ for the radius a and the radius b.

The uniformity of the group of light rays passing through the exit pupil EP is important for the relationship between the flattening and the ranging performance. As shown in FIG. **8**, for higher ranging precision, it is important to design so that the proportion of b'/b" to b/b approaches 1, where the position proportion of the light rays group passing through the aperture stop (the aperture stop S) is b/b.

At the optical axis vicinity, the change of the proportion of b'/b" to b/b is small; and problems due to distortion do not occur easily. On the other hand, at positions having high angles of view, the change of the proportion of b/b" to b/b is large; and ranging errors due to the distortion occur easily. Therefore, it is necessary for the circular cross section of the group of light rays not to flatten or to have a uniform interior as much as possible from the optical axis vicinity to positions having high angles of view.

Formulas and Parameters of Lens Configuration

In the following description, the optical axis direction of the lens is taken as the Z-direction; one normal direction of the optical axis is taken as the Y-direction; and a direction orthogonal to the Z-direction and the Y-direction is taken as the X-direction. The positive direction of the Z-direction is the direction from the object side of the main lens group toward the image plane.

Counting from the object side, the curvature radius of the ith surface (including the aperture stop surface) is Ri; the surface spacing along the optical axis between the ith and (i+1)th surfaces is Di; and counting from the object side, the refractive index and Abbe number of the jth lens are nj and vj, respectively.

$$z = \frac{cY^2}{1 + \sqrt{1 - (1+K)c^2Y^2}} + a_4Y^4 + a_6Y^6 + \ldots + a_{20}Y^{20} \qquad \text{[Formula 12]}$$

In Formula 12, c is the curvature of the aspherical surface vertex, K is the conic constant, al is the aspherical constant, Y is the height from the optical axis, and Z is the distance from the tangent plane to the points on the aspherical surface at the lens surface vertex.

Lens Configuration

A specific lens configuration will now be described.

FIG. **10** illustrates the configuration of the imaging lens according to the embodiment.

As shown in FIG. **10**, the imaging lens **110** includes the microlens array MLA (**14**) and the imaging optical system **12** which is the first optical system. In FIG. **10**, S is the aperture stop, R**1** is a surface (a first surface) on the object side of the first lens L**1**, R**2** is a surface (a second surface) on the image side of the first lens L**1**, R**3** is a surface (a third surface) on the object side of the second lens L**2**, R**4** is a surface (a fourth surface) on the image side of the second lens L**2**, R**5** is a surface (a fifth surface) on the object side of the third lens L**3**, R**6** is a surface (a sixth surface) on the image side of the third lens L**3**, R**7** is a surface (a seventh surface) on the object side of cover glass CG, R**8** is a surface (an eighth surface) on the image side of the cover glass CG, R**9** is a surface (a ninth surface) on the object side of the microlens array MLA, R**10** is a surface (a tenth surface) on the image side of the micro-lens array MLA, and DT is the imaging plane of the solid-

state imaging element **16**. The imaging plane is the plane in which the multiple pixels are provided.

The first surface R**1** opposes the aperture stop S. The second surface R**2** is provided between the first surface R**1** and the microlens array **14**.

The third surface R**3** opposes the second surface R**2**. The fourth surface R**4** is provided between the third surface R**3** and the microlens array MLA (**14**).

The fifth surface R**5** opposes the fourth surface R**4**. The sixth surface R**6** is provided between the fifth surface R**5** and the microlens array MLA (**14**).

The imaging lens **110** according to the embodiment can acquire both a high-precision range image and a good visible image.

The imaging optical system **12** includes the aperture stop S, the first lens L**1** having a positive refractive power, the second lens L**2** having a negative refractive power, and the third lens L**3** having a positive refractive power that are disposed in this order from the object side toward the image plane side. The lens group that includes the first lens L**1**, the second lens L**2**, and the third lens L**3** is the main lens.

The microlens array MLA (**14**) and the solid-state imaging element **16** are disposed on the image side of the imaging optical system **12**.

The microlens array MLA (**14**) is disposed between the imaging optical system **12** and the solid-state imaging element **16** including the multiple pixels. The microlens array MLA (**14**) is provided between the imaging optical system **12** and the focal position of the imaging optical system **12**. In other words, the microlens array MLA (**14**) is disposed on the object side of the focal position of the imaging optical system **12**. The microlens array MLA (**14**) includes the multiple microlens units **14a**. One microlens unit **14a** overlaps two or more pixels as viewed from the optical axis direction. Each of the multiple microlens units **14a** overlaps at least two pixels of the multiple pixels **16b** when projected onto the first plane **14p**.

In the embodiment, the main lens may include a lens that substantially does not have power. Also, the entire lens configuration may include a lens (e.g., the cover glass CG) that substantially does not have power.

Here, the orientations of the lenses of the main lens which is made of three lenses are as follows.

The curvature radius of the surface (the first surface) on the object side of the first lens L**1** is positive.

The curvature radii of the surface (the third surface) on the object side of the second lens L**2** and the surface (the fourth surface) on the image side of the second lens L**2** both are negative.

The curvature radii of the surface (the fifth surface) on the object side of the third lens L**3** and the surface (the sixth surface) on the image side of the third lens L**3** both are positive.

It is desirable for the arrangement between the imaging optical system **12** and the microlens array MLA (**14**) to be such that a demagnification ratio Nf when the microlens array MLA (**14**) demagnifies the image passing through the imaging optical system **12** is not less than 0.001 and not more than 0.87.

Thus, the basic configuration of the main lens is made of the positive first lens L**1**, the negative second lens L**2**, and the positive third lens L**3** and has a triplet lens configuration. By such a configuration, a thin imaging lens **110** having an appropriate backfocus and a short total lens length is obtained.

The number of lenses of the main lens is set to be three as a result of considering the performance as the highest priority and size reduction as a priority. In the case where the number

of lenses of the main lens is two or less, it is difficult to reduce the field curvature; and the peripheral performance degrades. The performance is better in the case where the number of lenses of the main lens is three or more. On the other hand, the total length increases, which may cause the weight to increase. Accordingly, the size of the main lens is reduced and good peripheral performance is provided by using a three-lens configuration in which it is possible to reduce the field curvature and distortion aberration.

It is desirable for at least one surface of the surfaces (R1 to R6) of the first lens L1, the second lens L2, and the third lens L3 included in the main lens to be an aspherical surface. Also, it is desirable for one surface on at least one selected from the object side and the image plane side to be an aspherical surface.

By using an aspherical surface in the positive first lens L1, using an aspherical surface having a negative refractive power in the second lens L2, and using an aspherical surface having a positive refractive power in the third lens L3, an imaging lens can be obtained in which various aberrations and particularly astigmatic aberration and distortion aberration are corrected, the total length of the lens system is short, and the imaging magnification of the imaging on the imaging plane DT of the solid-state imaging element 16 has a demagnification ratio for an incident angle on the microlens array MLA (14) of 30 degrees or less.

Further, by employing an aspherical surface in the second lens L2 having a negative refractive power and by appropriately disposing the spacing between the first lens L1 and the second lens L2 and the spacing between the second lens L2 and the third lens L3, various aberrations (comatic aberration, astigmatic aberration, and distortion aberration) of the screen peripheral portion distal to the optical axis can be corrected by utilizing the difference occurring between the transmission heights of the on-axis ray and the marginal ray.

It is desirable for the first lens L1 to be made of a glass material or a plastic material and for the second lens L2 and the third lens L3 to be made of a plastic material. Lenses that include a glass material and a plastic material also include lenses in which the surface of the plastic material is coated to prevent reflections and increase surface hardness.

The lens is small; and in the production of small lenses, plastic materials can be manufactured by injection molding, etc., and are more suitable to mass production than are glass materials. Further, plastic lenses are suitable to mass production with low manufacturing costs.

The aperture stop S adjusts the subject light amount passing through the microlens array MLA (14) and reaching the solid-state imaging element 16. The aperture stop S is disposed on the object side of the main lens. In other words, the aperture stop S, the first lens L1, the second lens L2, and the third lens L3 are disposed in the imaging lens 110 in order from the object side.

In the imaging lens 110, the incident angle onto the microlens array MLA (14) is reduced because the aperture stop S is disposed furthest on the object side. That is, the distance from the imaging plane to the exit pupil position can be longer for the type in which the aperture stop S is disposed furthest on the object side than for a middle-stop type in which the aperture stop is provided between the first lens L1 and the third lens L3.

In the case where the exit pupil is distal to the imaging plane, the chief ray of the light rays emitted from the final surface of the imaging lens 110 is incident on the microlens array MLA (14) at an angle that is nearly perpendicular, that is, the shift between the exit pupil of the imaging lens 110 and the exit pupils of the single lenses (the microlens units 14a) of

the microlens array MLA (14) can be reduced; and good aberration performance can be ensured.

The microlens array MLA (14) is disposed between the imaging optical system 12 and the solid-state imaging element 16. The image that passes through the microlens array MLA (14) is imaged on the solid-state imaging element 16 as a virtual image and is imaged at a demagnification ratio. Thereby, the original central performance and peripheral performance of the imaging lens 110 can be corrected to be even better.

Microlens Array

The microlens array MLA applied to the imaging lens 110 will now be described.

FIG. 11 is a schematic plan view illustrating the arrangement of the microlens units.

FIG. 12 to FIG. 13 are ray diagrams of the microlenses.

As shown in FIG. 11, the microlens array MLA (14) has a lens optical system arrangement using the multiple microlens units 14a. The lens optical system arrangement is such that the light in the axis direction of each of the microlens units 14a reaches the same position of each segment for each field of view. In the multiple optical system arrangement, the multiple optical systems are disposed uniformly from the center of the multiple optical system arrangement and are disposed, for example, in a hexagonal arrangement such as that shown in FIG. 11. In the case where the multiple microlens units 14a are packed in a hexagonal arrangement without gaps, the configuration of the outer circumference of each of the microlens units 14a is a hexagon.

The microlens array MLA (14) is formed of a refractive optical system. The microlens array MLA (14) is disposed between the imaging optical system 12 and the solid-state imaging element 16; and the imaging on the imaging element is at a virtual image magnification. The microlens array MLA (14) images light rays from the imaging optical system 12 having different angles of view on the solid-state imaging element 16. Because the microlens units 14a that are inside the microlens array MLA (14) are disposed in a hexagonal arrangement, the incident angle on the microlens unit 14a at the field-of-view periphery increases as the angle of view increases.

FIG. 12 shows a ray diagram when chief rays from the imaging optical system 12 are incident on the microlens array MLA (14) at an angle of 0 degrees.

FIG. 13 shows a ray diagram when chief rays from the imaging optical system 12 are incident on the microlens array MLA (14) at an angle of 30 degrees.

The refractive optical system that is formed in the microlens array MLA (14) is disposed between the imaging optical system 12 and the solid-state imaging element 16 at the appropriate virtual image magnification and is configured to have the appropriate focal length and F-number so that the light rays outside the field of view from the imaging optical system 12 can reach the imaging element as efficiently as possible.

In the imaging lens 110 according to the embodiment, the focal length and F-number of the microlens units 14a of the microlens array MLA (14) are set so that the light rays for which the incident angle of the chief rays on the image side are within 20 degrees to 30 degrees can efficiently reach the solid-state imaging element 16. As an example, Table 1 shows the specifications of a single lens (one microlens unit 14a) of the microlens array MLA (14) that images with a virtual image magnification of 0.5 times.

The parameters recited in Table 1 mean the following.

Nd is the d-line (587.6 nanometers (nm)) refractive index of the optical material of the lens.

vd is the Abbe number of the optical material of the lens for the d-line.

R is the effective radius (the millimeters (mm)), i.e., the radius of the circular region through which the light rays passes.

f is the focal length (mm).

TABLE 1

| fd (d-LINE FOCAL DISTANCE) 0.068 mm |
| (d-LINE WAVELENGTH λ: 587.56 nm) |
| F -NUMBER 2.2 |
| EFFECTIVE APERTURE DIAMETER Φ 0.030 mm |

SURFACE NUMBER	RADIAL THICKNESS	MATERIAL
0 (OBJECT SURFACE)	–0.05	AIR
1 (APERTURE STOP)	INFINITY (∞) 0.15	SYNTHETIC QUARTZ (Nd = 1.45844)
2	–0.03536	AIR
3 (IMAGE PLANE)	INFINITY	AIR

FIG. 14 is a ray diagram of a microlens.

FIG. 14 is the ray diagram of a single lens of the microlens array MLA shown in Table 1 for a chief ray angle of 0 degrees.

FIG. 15 shows aberration curves of the microlens.

FIG. 15 is the aberration diagram (for the chief ray angle of 0 degrees) of the single lens of the microlens array MLA shown in Table 1.

FIG. 16 is a ray diagram of the microlens.

FIG. 16 is the ray diagram of the single lens of the microlens array MLA shown in Table 1 for a chief ray angle of 20 degrees.

FIG. 17 shows aberration curves of the microlens.

FIG. 17 is the aberration diagram (for the chief ray angle of 20 degrees) of the single lens of the microlens array MLA shown in Table 1.

FIG. 18 is a ray diagram of the microlens.

FIG. 18 is the ray diagram of the single lens of the microlens array MLA shown in Table 1 for a chief ray angle of 30 degrees.

FIG. 19 shows aberration curves of the microlens.

FIG. 19 is the aberration diagram (for a chief ray angle of 30 degrees) of the single lens of the microlens array MLA shown in Table 1.

Condition Formulas of First Optical System (Imaging Optical System 12)

Condition Formulas of the imaging optical system 12 will now be described.

As shown in FIG. 10, the imaging lens 110 according to the embodiment includes, in order from the object side toward the image plane side, the aperture stop S, the first lens L1 that has a positive refractive power and a configuration in which the curvature radius of the surface on the object side is positive, the second lens L2 that has a negative refractive power and a configuration in which the curvature radii of the object-side surface and the image-side surface both are negative, and the third lens L3 that has a positive refractive power and is formed in a configuration in which the curvature radii of the object-side surface and the image-side surface both are positive; and the microlens array MLA (14) and the solid-state imaging element 16 are disposed rearward of these lenses.

In the imaging lens 110, the microlens array MLA (14) is disposed between the imaging optical system 12 and the solid-state imaging element 16. It is desirable for the magnification to be not less than 0.001 and not more than 0.87 in the case where the image formed by the imaging optical system 12 is to be demagnified by the microlens array MLA (14).

In such an optical system, the imaging lens 110 satisfies Condition Formulas (1) to (6) recited below.

$$0.6 < f1/f < 0.9 \tag{1}$$

$$1.0 < |f2|/f < 3.0 \tag{2}$$

$$2.0 < f3/f < 200 \tag{3}$$

$$TL/f < 1.3 \tag{4}$$

$$0 < D2/f < 0.2 \tag{5}$$

$$0 < D5/f < 0.5 \tag{6}$$

In Condition Formulas (1) to (6) recited above, f is the focal length of the entire system of the imaging optical system 12, f1 is the focal length of the first lens L1, f2 is the focal length of the second lens L2, f3 is the focal length of the third lens L3, TL is the distance between the aperture stop S and the imaging plane DT (the solid-state imaging element 16), D2 is the distance along the optical axis Ox between the second lens L2 and the third lens L3, and D5 is the thickness along the optical axis Ox of the third lens L3.

The basic characteristics of the lens configuration of the imaging lens 110 of the embodiment are made of the first lens which has the large positive power, the second lens L2 which has the relatively large negative power, and the third lens L3 which has the small positive power on the side most proximal to the image; and the power arrangement is a so-called positive-negative-positive triplet-type.

Further, the imaging lens 110 has the characteristic of performing achromatization to correct the chromatic aberration by the first lens L1 which has the large power, the second lens L2, and the third lens L3.

Accordingly, the first lens L1 and the second lens L2 have the effect of mainly correcting the spherical aberration, the comatic aberration, and the chromatic aberration proximal to the optical axis; and the third lens L3 has the effect of mainly correcting the distortion aberration, which is an off-axis aberrations, and maintaining good telecentricity.

Condition Formulas (1), (2), and (3) regulate the optimal refractive power arrangement for obtaining good optical performance in an imaging lens including few lenses.

Condition Formula (1) is a condition formula relating to the power of the first lens L1 for the combined focal length of the entire lens system. In the case where the power of the first lens L1 increases and the conditions are below the lower limit of Condition Formula (1), the comatic aberration and spherical aberration of the upper light ray, the comatic aberration, and the chromatic aberration become large; the performance undesirably degrades; correction is difficult; and the contrast of the entire screen decreases. Also, the curvature radius of the spherical surface of the lens of the first lens L1 becomes small; and the patterning is difficult.

On the other hand, in the case where the power of the first lens L1 decreases and the upper limit of Condition Formula (1) is exceeded, the backfocus becomes long; the total length of the lens system becomes large; compactness is lost; the comatic aberration of the light rays becomes large; and the performance undesirably degrades. Accordingly, it is difficult to reduce the total length of the imaging lens 110.

In Condition Formula (1), it is more favorable for the range to be $0.6 < f1/f < 0.8$, and even more favorable for the range to be $0.7 < f1/f < 0.8$.

Condition Formula (2) recited above is a condition formula relating to the absolute value of the power of the second lens L2 for the combined focal length the entire lens system. Condition Formula (2) regulates the negative power of the

second lens L2. It is necessary for the power of the negative second lens L2 to correct the aberration occurring due to the positive lens of the first lens L1. In the case where the negative power of the second lens L2 is set to be strong, the performance undesirably degrades because the negative power is excessive with respect to the correction effect of the negative lens. In particular, the chromatic aberration at the optical axis and the chromatic aberration of the magnification degrade. Moreover, the incident angle onto the imaging plane becomes too large. Therefore, it is favorable to set the negative power of the second lens L2 to be relatively weak. Accordingly, it is favorable to satisfy Condition Formula (2).

In the case where the power of the second lens L2 is strong and the conditions are below the lower limit of Condition Formula (2), the total length becomes long; the light ray height of the peripheral light rays becomes high; correction of the astigmatic aberration is difficult; and the contrast of the entire screen decreases. Moreover, the curvature radius of the spherical surface of the lens of the second lens L2 becomes small; and the patterning is difficult. Further, the incident angle onto the solid-state imaging element 16 becomes large; and it is unfavorably difficult to ensure the telecentric characteristics on the image plane side.

In the case where the upper limit of Condition Formula (2) is exceeded, the aberration correction balance of the on-axis aberrations and the off-axis aberrations degrades; and the off-axis aberrations cannot be corrected easily.

In Condition Formula (2), it is more favorable for the range to be 1.0<|f2|/f<2.5, and even more favorable for the range to be 1.5<|f2|/f<2.5.

Condition Formula (3) is a condition formula for regulating the refractive power of the positive third lens L3. Condition Formula (3) provides the balance between the refractive power of the positive first lens L1 and the refractive power of the negative second lens L2. In the case where the balance between the power of the first lens L1 and the power of the second lens L2 degrades, the total length of the imaging optical system increases or the performance undesirably degrades.

In the case where the power of the third lens L3 is large and the conditions are below the lower limit of Condition Formula (3), this is advantageous for size reduction, but it is difficult to correct the telecentricity and distortion aberration of the peripheral portion. Moreover, good performance cannot be ensured because the astigmatic aberration is under-corrected.

In the case where the power of the third lens L3 is small and the upper limit of Condition Formula (3) is exceeded, the power of the positive third lens L3 becomes too weak; the incident angle onto the solid-state imaging element 16 undesirably becomes too large; and the correction of the comatic aberration and the astigmatic aberration is insufficient. The backfocus of the entire lens system undesirably becomes long, which is disadvantageous for the reduction of the total length of the imaging optical system.

In Condition Formula (3), it is more favorable for the range to be 2.0<f3/f<150, and even more favorable for the range to be 2.0<f3/f<100.

Condition Formula (4) regulates the total length of the lens system of the imaging optical system 12. In the case where the upper limit of Condition Formula (4) is exceeded, compactness is not possible because the total lens length becomes large. Accordingly, according to the configuration satisfying Condition Formula (4), it is easy to make the imaging lens smaller and thinner.

In Condition Formula (4), it is more favorable when f/TL<1.2, and even more favorable when f/TL<1.0.

Condition Formula (5) is a condition formula for regulating the spacing between the second lens L2 and the third lens L3. In the case where the upper limit of Condition Formula (5) is exceeded, the aberration correction balance between the on-axis aberrations and the off-axis aberrations degrades; and the off-axis aberrations cannot be corrected easily. On the other hand, when the conditions are below the lower limit of Condition Formula (5), the peripheral performance degrades because a large field curvature occurs and the astigmatic aberration is not corrected sufficiently.

In Condition Formula (5), it is more favorable for the range to be 0<D2/f<0.15, and even more favorable for the range to be 0<D2/f<0.10.

Condition Formula (6) is a condition formula for regulating the thickness along the optical axis of the third lens L3. In the case where the upper limit of Condition Formula (6) is exceeded, the aberration correction balance between the on-axis aberrations and the off-axis aberrations degrades; and the magnification chromatic aberration cannot be corrected easily. Moreover, the chromatic aberration at the periphery cannot be corrected easily when combining with a MLA lens because the exit pupil configuration of the off-axis light rays greatly deforms.

In Condition Formula (6), it is more favorable for the range to be 0<D5/f<0.4, and even more favorable for the range to be 0<D5/f<0.3.

Also, in the imaging lens 110 according to the embodiment, it is desirable for the height position of the chief ray passing through the second lens L2 to satisfy Condition Formula (7) recited below.

$$0.3 < hc(G2R)D(D1+D2+D3) < 0.6 \qquad (7)$$

In Condition Formula (7), hc(G2R) is the height at which the chief ray of the off-axis light rays of the maximum angle of view passes through the surface (the fourth surface) on the image side of the second lens L2. In other words, hc(G2R) is the distance between the optical axis Ox and the position where the chief ray of the off-axis light rays and the fourth surface intersect. D1+D2+D3 is the distance along the optical axis Ox from the aperture stop S to the surface (the fourth surface) on the image side of the second lens L2. D1 is the thickness along the optical axis Ox of the first lens L1. D2 is the air space along the optical axis Ox between the first lens L1 and the second lens L2. In other words, D2 is the product of the distance along the optical axis Ox between the first lens L1 and the second lens L2 and the refractive index of the region between the first lens L1 and the second lens L2. D3 is the thickness along the optical axis Ox of the second lens L2.

Here, Condition Formula (7) is a condition formula for controlling the height at which the off-axis chief ray passes through the second lens L2. Condition Formula (7) is the condition for preventing the occurrence of the chromatic aberration as much as possible when the off-axis light rays that pass through the imaging lens 110 are incident on the microlens array MLA (14); and Condition Formula (7) limits the configuration of the exit pupil of the off-axis light rays.

In the case where the upper limit of Condition Formula (7) is exceeded and the height at which the chief ray of the off-axis light rays of the maximum angle of view passing through the surface (the fourth surface) on the image side of the second lens L2 becomes high, the incident height on the surface (the fifth surface) on the object side of the third lens L3 becomes high; and it is necessary to relax the refractive power of the surface (the fifth surface) on the object side of the third lens L3. Although the occurrence of the comatic aberration increases because the refractive power of this portion is

weakened, the configuration of the exit pupil of the off-axis light rays does not change greatly.

In the case where the conditions are below the lower limit of Condition Formula (7), the light ray height at the surface (the fifth surface) on the object side of the third lens L3 decreases; and it is necessary to increase the refractive power of the light rays at the third lens L3. Because the refractive power of this portion is increased, it is difficult to ensure the incident angle of the light rays toward the prescribed image height, i.e., the CRA (Chief Ray Angle (the incident angle of the chief ray onto the image plane)). Because it is necessary to increase the negative refractive power of the second lens L2 to ensure the incident height on the third lens L3, a large comatic aberration of the off-axis light rays occurs; and the configuration of the exit pupil of the off-axis light rays undesirably changes greatly.

In Condition Formula (7), it is more favorable for the range to be $0.3 < hc(G2R)/D(D1+D2+D3) < 0.5$, and even more favorable for the range to be $0.3 < hc(G2R)D(D1+D2+D3) < 0.4$.

The configuration of the exit pupil is the configuration of the off-axis light rays at the exit pupil plane of the imaging optical system **12**. The exit pupil plane is, for example, the plane at which the exit pupil of the imaging optical system **12** is imaged. The configuration of the exit pupil is, for example, treated as an ellipse. In such a case, the configuration of the exit pupil has a first diameter and a second diameter. The first diameter is the diameter along the first direction (the X-direction) in the exit pupil plane of the exit pupil. The second diameter is the diameter along the second direction (the Y-direction) in the exit pupil plane of the exit pupil.

In the imaging lens **110** according to the embodiment, it is desirable for the exit pupil configuration at the position of the exit pupil to satisfy Condition Formula (8) recited below.

$$0 \leq \rho < 0.3 \qquad (8)$$

In Condition Formula (8), ρ is the flattening. The flattening ρ is $\rho = |1 - b/a|$. a is the radius in the first direction orthogonal to the optical axis of the off-axis light rays passing through the exit pupil at the exit pupil position. b is the radius in the second direction (the direction orthogonal to the first direction) orthogonal to the optical axis of the off-axis light rays passing through the exit pupil at the exit pupil position.

a is ½ times the first diameter. When the exit pupil is treated as substantially a circle or an ellipse, the first diameter is the major diameter of the length of the pupil at the exit pupil position. The radius a is expressed by a=hx(EXTPURX).

b is ½ times the second diameter. When the exit pupil is treated as substantially a circle or an ellipse, the second diameter is the minor diameter of the length of the pupil at the exit pupil position. The radius b is expressed by b=(hy(EXT-PiUR)−hy(EXTPiDW))/2.

h(EXTPiCR) is the height at which the chief ray of the off-axis light rays passes through the exit pupil plane.

h(EXTPiUR) is the height at which the upper light ray of the off-axis light rays passes through the exit pupil plane.

h(EXTPiDW) is the height at which the lower light ray of the off-axis light rays passes through the exit pupil plane.

hx(EXTPURX) is the length in the depth direction of the light rays in the plane perpendicular to the chief ray of the off-axis light rays that pass through the exit pupil plane. hx(EXTPURX) is ½ times the length along the first direction (the X-direction) of the off-axis light rays L**23** in the exit pupil plane.

For example, hy(EXTPiUR) is the height in the second direction at which the upper light ray of the off-axis light rays passes through the exit pupil plane. hy(EXTPiUR) is the

distance along the second direction (the Y-direction) between the optical axis Ox and the position where the upper light ray L**23**u passes through the exit pupil plane. hy(EXTPiDW) is the height in the second direction at which the lower light ray of the off-axis light rays passes through the exit pupil plane. hy(EXTPiDW) is the distance along the second direction between the optical axis Ox and the position where the lower light ray L**23**d passes through the exit pupil plane.

Condition Formula (8) is the condition formula for the configuration of the exit pupil at the position of the exit pupil of the imaging lens **110** according to the embodiment.

When the light rays from the imaging optical system **12** is demagnified and imaged onto the solid-state imaging element by the microlens array MLA (**14**), it is ideal for the configuration of the exit pupil of the imaging optical system **12** and the configuration of the entrance pupil of the single lens on the microlens array MLA (**14**) to match so that the light rays efficiently reaches the solid-state imaging element **16**.

However, actually, because the arrangement of the single lenses of the microlens array MLA (**14**) has hexagonal packing density, even if single lens centers on the microlens array MLA (**14**) are aligned with the center of the solid-state imaging element **16**, the chief ray of the off-axis light rays that has a large angle of view has a large incident angle with respect to the optical axes of the single lenses of the microlens array MLA (**14**) and is incident at a tilt of 20 degrees to 30 degrees with respect to the optical axis of the microlens array MLA (**14**); and therefore, it is difficult to align the entrance pupil position of the microlens array MLA (**14**) and the exit pupil position of the imaging optical system **12**.

The pupil configuration of the off-axis light rays that is emitted tilted with respect to the imaging optical system **12** is an ellipse (a configuration such as a laterally-long cat's eye) due to the effect of vignetting. To cause the off-axis light rays from the imaging optical system **12** to be incident efficiently on the single lenses of the microlens array MLA (**14**) as much as possible, it is necessary for the configuration of the exit pupil from the imaging optical system **12** to be a configuration as close to a circle as possible. Condition Formula (8) regulates such a pupil configuration.

In the case where the upper limit of Condition Formula (8) is exceeded, the configuration of the exit pupil of the imaging optical system **12** shifts greatly from the configuration of the exit pupil of the single lenses of the microlens array MLA (**14**). Therefore, it is difficult to cause the light rays to pass through the microlens array MLA (**14**) and efficiently reach the solid-state imaging element **16**.

In Condition Formula (8), it is more favorable for the range to be $0 \leq \rho < 0.2$, and even more favorable for the range to be $0 \leq \rho < 0.15$.

In the imaging lens **110** according to the embodiment, it is desirable for Condition Formula (9) recited below to be satisfied.

$$0 \leq \nu - \nu 2 \qquad (9)$$

In Condition Formula (9), ν1 is the Abbe number of the first lens L**1**; and ν2 is the Abbe number of the second lens L**2**.

Condition Formula (9) regulates the Abbe numbers of the materials included in the positive first lens L**1** and the negative second lens L**2**. By satisfying Condition Formula (9), it is possible to correct the chromatic aberration at the optical axis and the off-axis chromatic aberration of the magnification.

The imaging lens **110** according to the embodiment may be configured to satisfy Condition Formula (10) recited below.

$$20° \leq \alpha i \leq 30° \qquad (10)$$

In Condition Formula (10), α_i is the incident angle of the chief ray of the off-axis light rays onto the imaging plane DT at the maximum angle of view (the maximum image height).

In the imaging lens **110** according to the embodiment, in the case where the solid-state imaging element **16** and the microlens array MLA (**14**) are used in combination, when the off-axis light rays that is emitted from the imaging optical system **12** is incident at a large angle with respect to the microlens array MLA (**14**) and passes through the microlens array MLA (**14**) to be imaged on the solid-state imaging element **16**, the angle of view of the off-axis light rays that can be tolerated by the microlens array MLA (**14**) undesirably shifts greatly; and the brightness of the image is undesirably different between the image central portion and the image peripheral portion. When the incident angle on the microlens array MLA (**14**) is small, this problem is reduced, but the total length of the optical system undesirably becomes large. Therefore, it is favorable to satisfy Condition Formula (10).

Thus, according to the imaging lens **110** of the embodiment and the solid state imaging device **1** that includes the imaging lens **110**, a low number of lenses and a simple lens configuration are possible; high performance such as the F-number being small, etc., can be achieved; and the lens system itself can be compact. Also, both a high-precision range image and a good visible image can be acquired.

The imaging lens **110** and the solid state imaging device **1** according to the embodiment are applicable to various electronic devices such as, for example, a portable terminal such as a mobile telephone, a tablet terminal, a digital camera, or the like, a video device, an industrial robot, a robot arm, a medical device such as an endoscope, etc.

A numerical example of the imaging optical system **12** will now be described as an example.

First Example

FIG. **20** illustrates the configuration of an imaging lens according to a first example.

FIG. **21** and FIG. **22** are various aberration diagrams of the imaging lens according to the first example.

FIG. **23** illustrates the exit pupil position of the imaging lens according to the first example.

FIG. **24** illustrates the configurations and numerical values of the exit pupils of the imaging lens according to the first example.

Table 2 recited below illustrates the curvature radius Ri, the spacing Di, the refractive index nd, and the dispersion value vd for the surfaces of the imaging optical system **12** according to the first example.

TABLE 2

f 4.56 mm F-NUMBER = 2.24 ω = 32°				
SURFACE	Ri	Di	nd	vd
(APERTURE STOP(s)	INFINITY	0.00000		
1	1.56915	1.08739	1.52528	55.95
2	6.38856	0.47016		
3	−2.31466	0.39136	1.61421	25.58
4	−5.17862	0.42580		
5	3.24713	1.25821	1.52528	55.95
6	3.76960	0.33796		
7 (CG)	INFINITY	0.30000	1.51680	64.17
8	INFINITY	0.50000		

TABLE 2-continued

f 4.56 mm F-NUMBER = 2.24 ω = 32°				
SURFACE	Ri	Di	nd	vd
9 (MLA)	INFINITY	0.15000	1.15841	67.83
10	INFINITY	0.30000		

The following is the aspherical surface data of the imaging optical system **12** according to the first example.

First surface:
K=−0.20635
a4=0.0026523617
a6=0.0007572847
a8=0.0291724751
a10=−0.088437280
a12=0.0936050540
a14=−0.037365195
Second surface:
K=−26.44687
a4=−0.019607836
a6=−0.059941816
a8=0.0683856688
a10=−0.23123545
a12=0.1976539207
a14=−0.055919811
Third surface:
K=−1.07394
a4=−0.186694844
a6=−0.209825776
a8=0.6492044946
a10=−0.648835892
a12=−0.527660809
a14=1.5596893775
a16=−0.812155745
Fourth surface:
K=10.90861
a4=−0.257661814
a6=0.2041165409
a8=−0.066789470
a10=0.0058690518
a12=0.0254239177
a14=0.0371547120
a16=−0.019455088
Fifth surface:
K=−16.94786
a4=−0.56635536
a6=0.670840323
a8=−1.47204909
a10=1.549708682
a12=0.150886336
a14=−1.06494220
a16=−0.72016649
a18=1.717681955
a20=−0.65311677
Sixth surface:
K=−6.37821
a4=−0.1369577
a6=−0.02239878
a8=0.033002391
a10=−0.01986092
a12=0.008995937
a14=−0.000399589
a16=0.001095174
a18=−0.00012917

a20=−0.00000215
f1/f=0.801
|f2|/f=1.561
f3/f=5.311
f/TL=1.121
D2/f=0.093
D5/f=0.276
hc(G2R)/(D1+D2+D3)=0.418
ν1−ν2=30.37
ρ=0.163
CRA (incident angle of chief ray onto image plane) (angle of view of 31 degrees)=27.168°.

As described below, Condition Formulas (1) to (10) recited above are satisfied in the example. As recited above, it can be seen that the imaging optical system **12** according to the first example has good performance.

Second Example

FIG. **25** illustrates the configuration of an imaging lens according to a second example.

FIG. **26** and FIG. **27** are various aberration diagrams of the imaging lens according to the second example.

FIG. **28** illustrates the exit pupil position of the imaging lens according to the second example.

FIG. **29** illustrates the configurations and numerical values of the exit pupils of the imaging lens according to the second example.

Table 3 recited below shows the curvature radius Ri, the spacing Dic, the refractive index nd, and the dispersion value νd for the surfaces of the imaging optical system **12** according to the second example.

TABLE 3

		f 4.59 mm F-NUMBER = 2.24 ω = 32.03°		
SURFACE	Ri	Di	nd	νd
(APERTURE STOP(s))	INFINITY	0.00000		
1	1.489118	0.82969	1.54413	55.98
2	4.730869	0.55525		
3	−2.670959	0.39136	1.61421	25.58
4	−5.242258	0.47714		
5	4.805683	1.29150	1.54413	65.98
6	4.431227	0.53605		
7 (CG)	INFINITY	0.30000	1.51680	64.17
8	INFINITY	0.30000		
9 (MLA)	INFINITY	0.15000	1.45844	67.83
10	INFINITY	0.31326		

The aspherical surface data of the imaging optical system **12** according to the second example is as follows.
First surface:
K=−0.38494
a4=0.0171071031
a6=0.0036350659
a8=0.0363451319
a10=−0.085885467
a12=0.0917809567
a14=−0.034697572
a16=−0.000087116
Second surface:
K=14.26463
a4=−0.015181501
a6=−0.019061020
a8=0.0440043763

a10=−0.145180982
a12=0.1838550056
a14=−0.101532532
Third surface:
K=0.84715
a4=−0.105398051
a6=−0.095650008
a8=0.5354757811
a10=−0.652596321
a12=−0.164674543
a14=0.9793333945
a16=−0.606186909
Fourth surface:
K=4.05765
a4=−0.167280149
a6=0.1612834476
a8=−0.036538152
a10=0.0077283823
a12=0.0091569156
a14=0.0138977112
a16=−0.00545494
Fifth surface:
K=−83.08277
a4=−0.36728695
a6=0.318695236
a8=−1.06102987
a10=1.371938273
a12=0.013873971
a14=−0.99872086
a16=−0.61335553
a18=1.68667291
a20=−0.67437564
Sixth surface:
K=−32.8186
a4=−0.0721218
a6=−0.06358615
a8=0.037227031
a10=−0.00605082
a12=−0.00148953
a14=−0.00135596
a16=0.001342416
a18=−0.00036955
a20=0.000031273
f1/f=0.794
|f2|/f=2.033
f3/f=103.683
TL/f=1.096
D2/f=0.104
D5/f=0.281
hc(G2R)/(D1+D2+D3)=0.467
ν1−ν2=30.37
ρ=0.179
CRA (incident angle of chief ray onto image plane) (angle of view of 31 degrees)=26.12°.

As described below, Condition Formulas (1) to (10) recited above are satisfied in the example. As recited above, it can be seen that the imaging optical system **12** according to the second example has good performance.

Third Example

FIG. **30** illustrates the configuration of an imaging lens according to a third example.

FIG. **31** and FIG. **32** are various aberration diagrams of the imaging lens according to the third example.

FIG. **33** illustrates the exit pupil position of the imaging lens according to the third example.

The aspherical surface data of the imaging optical system 12 according to the fourth example is as follows.

First surface:
K=−0.14556925
a4=0.00865748
a6=0.01535309
a8=0.022838803
a10=−0.0807432
a12=0.101719532
a14=−0.04098285
Second surface:
K=−64.93822
a4=0.065296325
a6=−0.04793898
a8=0.072653147
a10=−0.13704764
a12=0.185529421
a14=−0.11017364
Third surface:
K=0.421682639
a4=−0.0838032
a6=−0.15298818
a8=0.671464289
a10=−0.7491886
a12=−0.3598329
a14=1.378890211
a16=−0.8109447
Fourth surface:
K=−9.97319261
a4=−0.23169433
a6=0.181826267
a8=−0.06421142
a10=0.018411689
a12=0.002007272
a14=0.007578708
a16=−0.00430411
Fifth surface:
K=−41.3232311
a4=−0.38012889
a6=0.473270827
a8=−1.27740830
a10=1.500018546
a12=0.119769405
a14=−1.18479210
a16=−0.66533645
a18=1.948821319
a20=−0.85388631
Sixth surface:
K=−9.37636765
a4=−0.17333756
a6=0.0800088524
a8=−0.06665131
a10=0.02565206
a12=0.006098033
a14=−0.00750137
a16=0.000734333
a18=0.000627152
a20=−0.00013698
f1/f=0.834
|f2|/f=2.560
f3/f=101.258
TL/f=1.139
D2/f=0.119
D5/f=0.286
hc(G2R)/(D1+D2+D3)=0.462
v1−v2=30.37
ρ=0.174

CRA (incident angle of chief ray onto image plane) (angle of view of 31 degrees)=25.3°.

As described below, Condition Formulas (1) to (10) recited above are satisfied in the example. As recited above, it can be seen that the imaging optical system 12 according to the fourth example has good performance.

Table 6 shows the values of the Condition Formulas of the examples.

TABLE 6

	FIRST EXAMPLE	SECOND EXAMPLE	THIRD EXAMPLE	FOURTH EXAMPLE
CONDITION FORMULA (1)	0.8	0.794	0.77	0.834
CONDITION FORMULA (2)	1.56	2.03	1.26	2.57
CONDITION FORMULA (3)	5.31	103.68	3.55	103.93
CONDITION FORMULA (4)	1.12	1.095	1.12	1.12
CONDITION FORMULA (5)	0.093	0.104	0.081	0.119
CONDITION FORMULA (6)	0.276	0.281	0.285	0.284
CONDITION FORMULA (7)	0.42	0.467	0.433	0.46
CONDITION FORMULA (8)	0.16	0.17	0.16	0.16
CONDITION FORMULA (9)	30.37	30.37	30.37	30.37
CONDITION FORMULA (10)	27.2°	26.1°	25.8°	25.2°

As shown in Table 6, each of Condition Formulas (1) to (10) recited above is satisfied in the first to fourth examples.

According to the imaging lens and the solid state imaging device according to the embodiment as described above, both a high-precision range image and a good visible image can be acquired.

Although an embodiment and examples are described hereinabove, the invention is not limited to these examples. For example, although the embodiment and examples recited above illustrate examples in which the cover glass (CG) and the microlens array (MLA) are provided, a configuration that includes only the microlens array (MLA) may be used. Also, the values illustrated in the examples recited above are merely examples; and other values may be used as long as the conditions of the invention are satisfied. Further, additions, deletions, or design modifications of the components or appropriate combinations of the features of the embodiment appropriately made by one skilled in the art in regard to the embodiment and the examples described above are within the scope of the invention to the extent that the spirit of the invention is included.

While certain embodiments have been described, these embodiments have been presented by way of example only, and are not intended to limit the scope of the inventions. Indeed, the novel embodiments described herein may be embodied in a variety of other forms; furthermore, various omissions, substitutions and changes in the form of the embodiments described herein may be made without departing from the spirit of the inventions. The accompanying claims and their equivalents are intended to cover such forms or modifications as would fall within the scope and spirit of the invention.

What is claimed is:

1. An imaging lens, comprising:

a first optical system including an optical axis; and

a microlens array provided between the first optical system and an imaging element,

the microlens array including a plurality of microlens units provided in a first plane,

the imaging element including a plurality of pixel groups,

each of the pixel groups including a plurality of pixels,

the microlens units respectively overlapping the pixel groups when projected onto the first plane,

the first optical system including:

an aperture stop;

a first lens provided between the aperture stop and the microlens array, the first lens having a first surface, a second surface, and a positive refractive power, the first surface opposing the aperture stop, the second surface being provided between the first surface and the microlens array;

a second lens provided between the first lens and the microlens array, the second lens having a third surface, a fourth surface, and a negative refractive power, the third surface opposing the second surface, the fourth surface being provided between the third surface and the microlens array; and

a third lens provided between the second lens and the microlens array, the third lens having a fifth surface, a sixth surface, and a positive refractive power, the fifth surface opposing the fourth surface, the sixth surface being provided between the fifth surface and the microlens array,

a curvature radius of the first surface being positive,

each of a curvature radius of the third surface and a curvature radius of the fourth surface being negative,

each of a curvature radius of the fifth surface and a curvature radius of the sixth surface being positive,

at least one selected from the first to sixth surfaces having an aspherical configuration,

Formulas (1) to (6) being satisfied, where

f is a focal length of the first optical system,

f1 is a focal length of the first lens,

f2 is a focal length of the second lens,

f3 is a focal length of the third lens,

TL is a distance between the aperture stop and the imaging element,

D2 is a distance along the optical axis between the second lens and the third lens, and

D5 is a thickness along the optical axis of the third lens:

$$0.6 < f1/f < 0.9 \tag{1}$$

$$1.0 < |f2|/f < 3.0 \tag{2}$$

$$2.0 < f3/f < 200 \tag{3}$$

$$f/TL < 1.3 \tag{4}$$

$$0 < D2/f < 0.2 \tag{5}$$

$$0 < D5/f < 0.5 \tag{6}$$

2. The lens according to claim 1, wherein

the microlens array demagnifies an image formed by the first optical system, and

a demagnification ratio of the image due to the microlens array is not less than 0.001 and not more than 0.87.

3. The lens according to claim 1, wherein Formula (7) is satisfied, where

a distance between the optical axis and a position where a chief ray of off-axis light rays intersects the fourth surface is hc(G2R), the off-axis light rays intersecting the optical axis,

a distance along the optical axis between the aperture stop and the fourth surface is D1+D2+D3,

D1 is a thickness along the optical axis of the first lens,

D2 is a product of a first distance and a first refractive index, the first distance being a distance along the optical axis between the first lens and the second lens, the first refractive index being an index of a region between the first lens and the second lens, and

D3 is a thickness along the optical axis of the second lens:

$$0.3 < hc(G2R)/(D1+D2+D3) < 0.6 \tag{7}$$

4. The lens according to claim 1, wherein

the first lens includes at least one selected from glass and a resin, and

each of the second lens and the third lens includes a resin.

5. The lens according to claim 1, wherein

a configuration of off-axis light rays at an exit pupil plane of the first optical system has a first diameter and a second diameter when the configuration is treated as an ellipse, the off-axis light rays intersecting the optical axis, the first diameter being along a first direction in the exit pupil plane, the second diameter being along a second direction perpendicular to the first direction and in the exit pupil plane,

Formula (8) is satisfied, where

a is ½ times the first diameter,

b is ½ times the second diameter,

ρ is flattening,

a=hx(EXTPURX),

b=(hy(EXTPiUR)−hy(EXTPiDW))/2, and

ρ=|1−b/a|,

the off-axis light rays includes:

an upper light ray;

a lower light ray positioned between the upper light ray and the optical axis at the exit pupil plane; and

a chief ray positioned between the upper light ray and the lower light ray at the exit pupil plane,

hy(EXTPiUR) is a distance along the second direction between the optical axis and a position where the upper light ray passes through the exit pupil plane,

hy(EXTPiDW) is a distance along the second direction between the optical axis and a position where the lower light ray passes through the exit pupil plane, and

hx(EXTPURX) is ½ times a length along the first direction of the off-axis light rays at the exit pupil plane:

$$0 \le \rho < 0.3 \tag{8}$$

6. The lens according to claim 1, wherein

Formula (9) is satisfied, where

ν1 is an Abbe number of the first lens, and

ν2 is an Abbe number of the second lens:

$$0 \le \nu1 - \nu2 \tag{9}$$

7. The lens according to claim 1, wherein

Formula (10) is satisfied, where

αi is an incident angle of a chief ray on a surface where the pixels are provided, and

the chief ray is a chief ray of off-axis light rays at a maximum angle of view, the off-axis light rays traveling in a direction intersecting the optical axis:

$$20° \le \alpha i \le 30° \tag{10}$$

8. The lens according to claim **1**, further comprising an optical filter provided between the first optical system and the microlens array.

9. The lens according to claim **1**, wherein the imaging element is provided between the first optical system and a virtual imaging point of the first optical system.

10. A solid state imaging device, comprising:

the imaging lens according to claim **1**; and

a solid-state imaging element to convert light passing through the imaging lens into an electrical signal.

11. The device according to claim **10**, wherein the solid-state imaging element outputs a plenoptic image.

12. The device according to claim **11**, wherein

the plenoptic image includes a plurality of picture cells,

each of the picture cells corresponds to one selected from a plurality of colors, the colors being different from each other, and

the device adjusts a signal balance between the colors of the plenoptic image.

13. The device according to claim **11**, wherein

the plenoptic image includes a plurality of picture cells including a first picture cell corresponding to a signal of a first color, and

the device estimates a signal of a second color of the first picture cell by referring to a picture cell disposed around the first picture cell, the second color being different from the first color.

14. The device according to claim **11**, wherein

the plenoptic image includes a plurality of image points corresponding a first point on a subject, and

the device calculates a correspondence between the first point and each of the image points.

15. The device according to claim **14**, wherein

the device calculates a two-dimensional image by synthesizing a picture cell value of each of the image points based on the correspondence and calculating a post-synthesis signal corresponding to the first point.

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